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(12) **United States Patent**
Hussein et al.

(10) **Patent No.: US 10,984,937 B2**
(45) **Date of Patent: Apr. 20, 2021**

(54) **ELECTROMAGNETIC TOOL FOR TRANSFERRING MICRO DEVICES AND METHODS OF FABRICATION**

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(73) Assignee: **LuxNour Technologies Inc.**, Portland, OR (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 147 days.

(21) Appl. No.: **16/129,730**

(22) Filed: **Sep. 12, 2018**

(65) **Prior Publication Data**

US 2020/0082965 A1 Mar. 12, 2020

(51) **Int. Cl.**

H01F 7/128	(2006.01)
H01L 21/04	(2006.01)
H01L 33/56	(2010.01)
H01F 7/06	(2006.01)
H01F 7/02	(2006.01)
B23Q 3/18	(2006.01)
B23Q 3/00	(2006.01)

(52) **U.S. Cl.**

CPC ***H01F 7/064*** (2013.01); ***B23Q 3/00*** (2013.01); ***B23Q 3/18*** (2013.01); ***H01F 7/0242*** (2013.01)

(58) **Field of Classification Search**

CPC H01F 7/064; H01F 7/128; H01F 7/206; H01L 21/042; H01L 33/56; H01L 21/67144; H01L 21/681; H01L 25/0753; H01L 33/0095; H01L 21/67; B23Q 3/00; B23Q 3/06; B23Q 3/061

USPC 335/285, 286, 289

See application file for complete search history.

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2020/0083069	A1 *	3/2020	Hussein	H01L 25/0753

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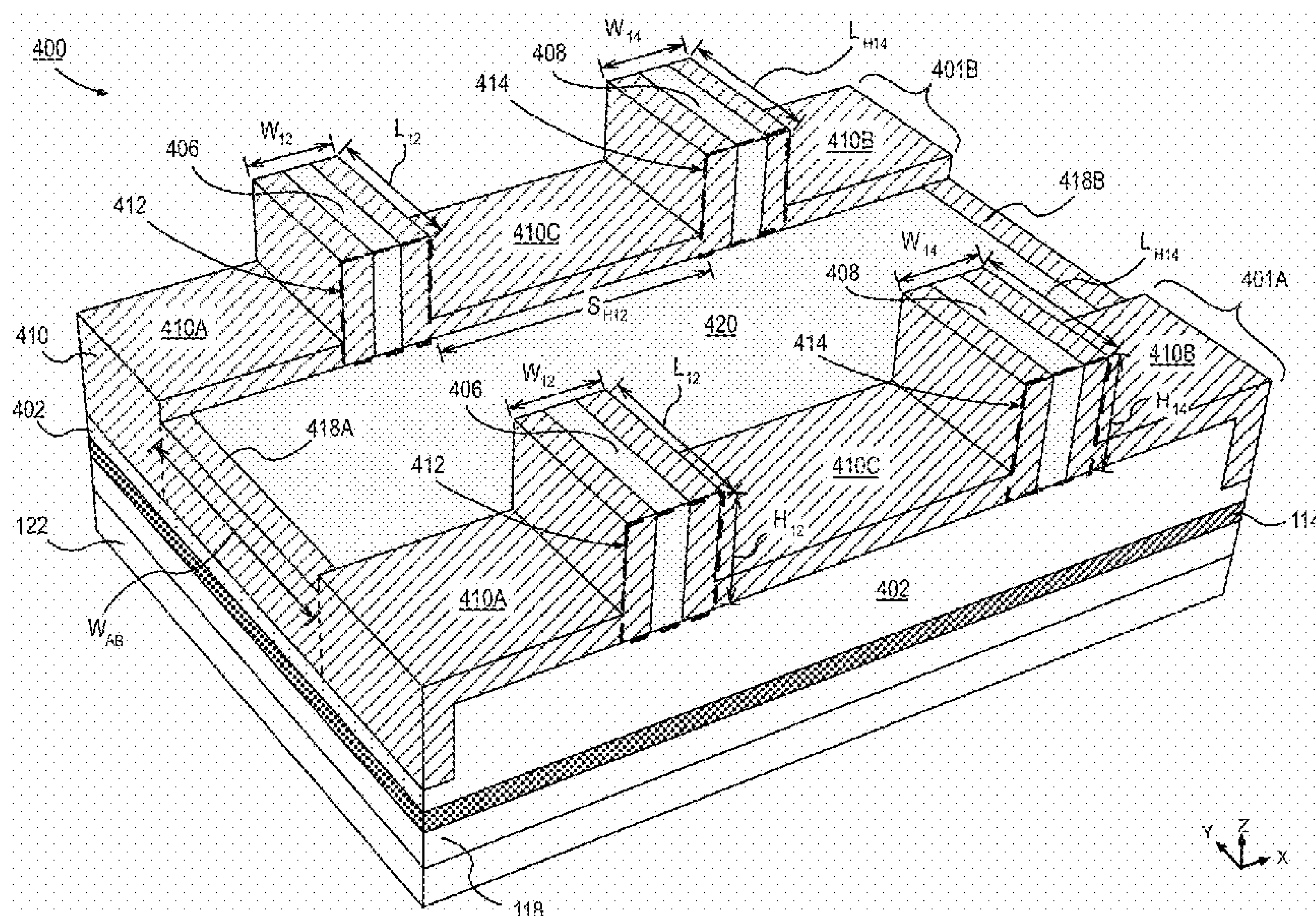
Primary Examiner — Bernard Rojas

(74) *Attorney, Agent, or Firm* — Green, Howard & Mughal LLP

(57) **ABSTRACT**

An electromagnetic apparatus includes a non-magnetic body structure above a substrate. The electromagnetic apparatus further includes at least one isolation structure including a dielectric material on a portion of the body structure and a magnetic structure having two separate portions, one on each side of the isolation structure. A first magnetic structure portion is on a first sidewall of the isolation structure on an upper surface and on a first sidewall of the body structure and a second magnetic structure portion is on an opposite second sidewall of the isolation structure onto an upper surface and on to a second sidewall of the body structure. The electromagnetic apparatus further includes an electromagnet on a side opposite to the isolation structure. The electromagnet is coupled with the magnetic structure and is a source of the magnetic flux lines when energized.

21 Claims, 32 Drawing Sheets



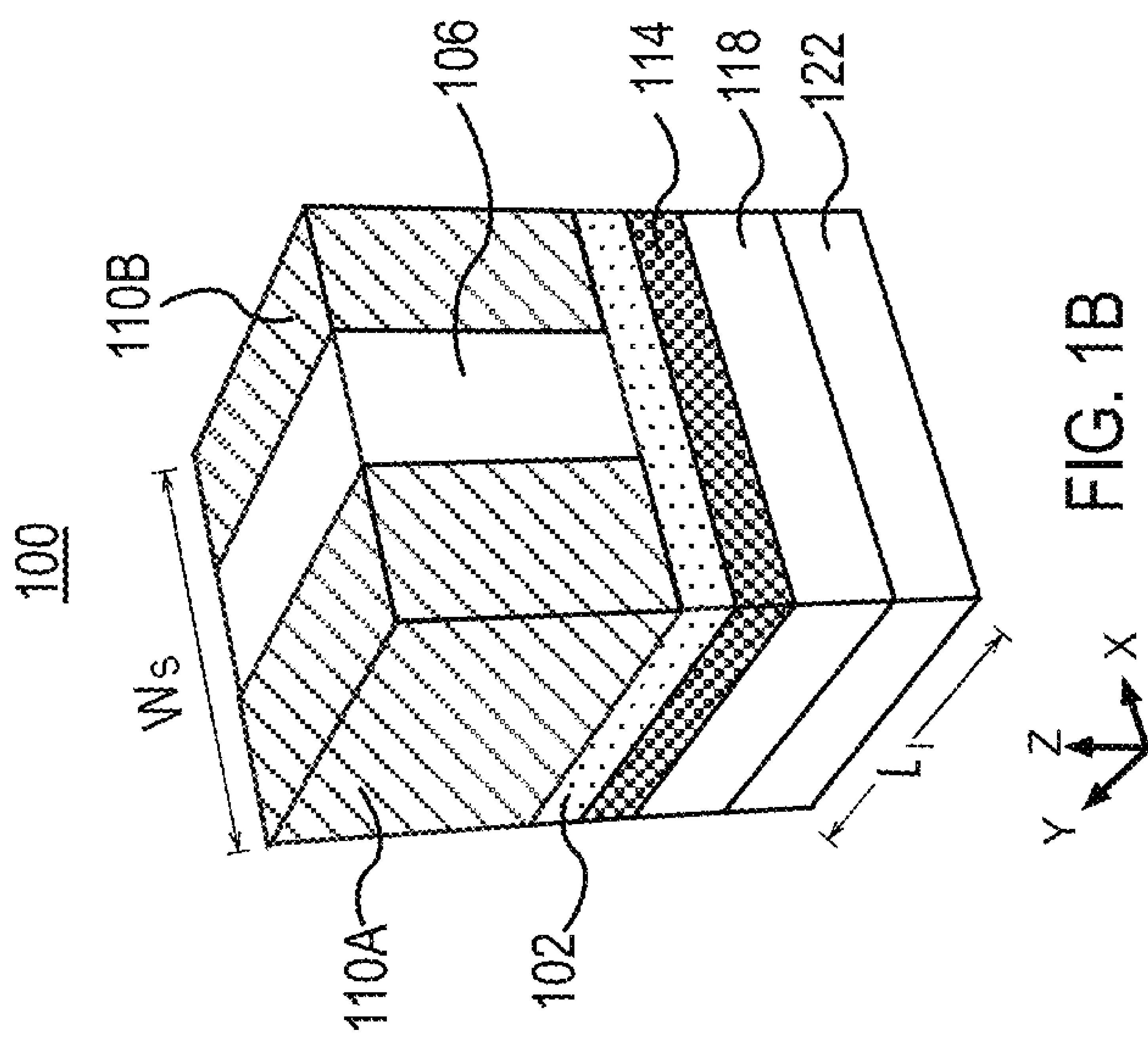


FIG. 1B

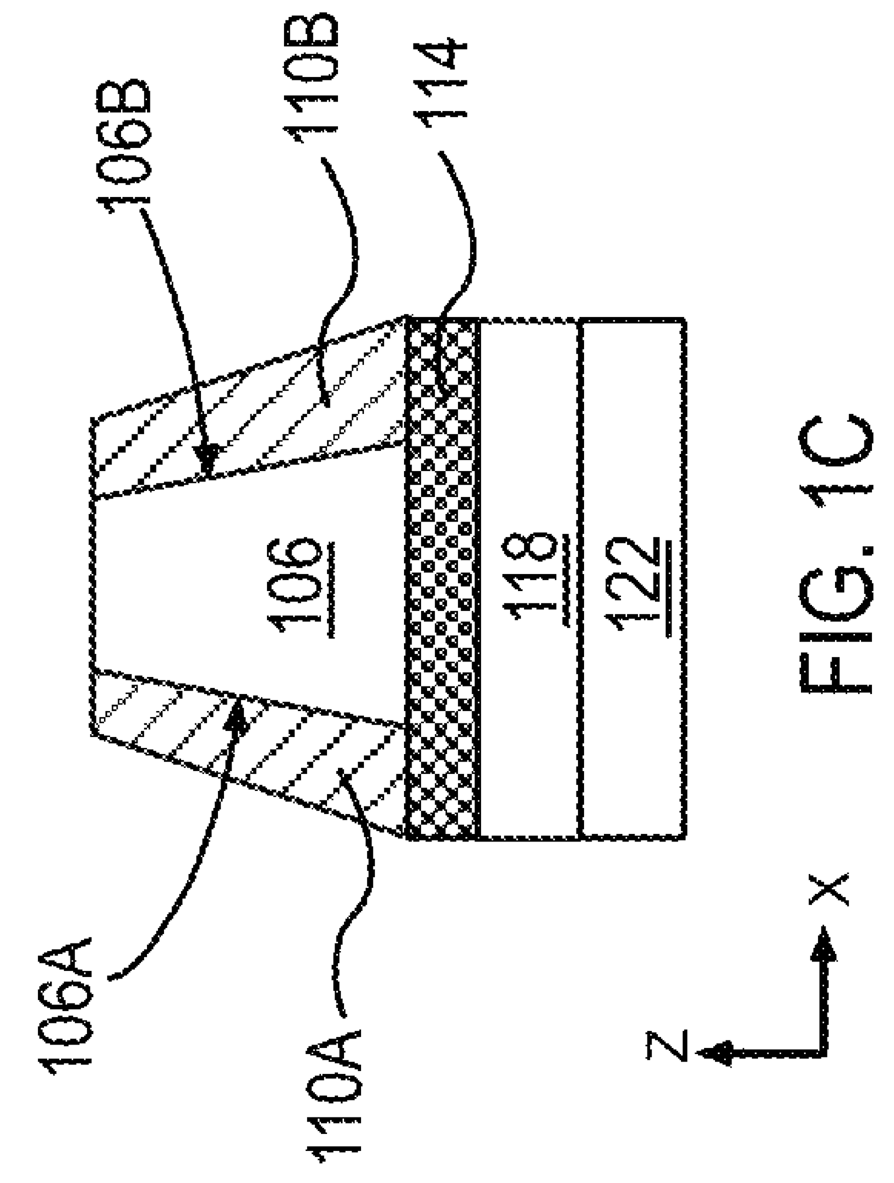


FIG. 1C

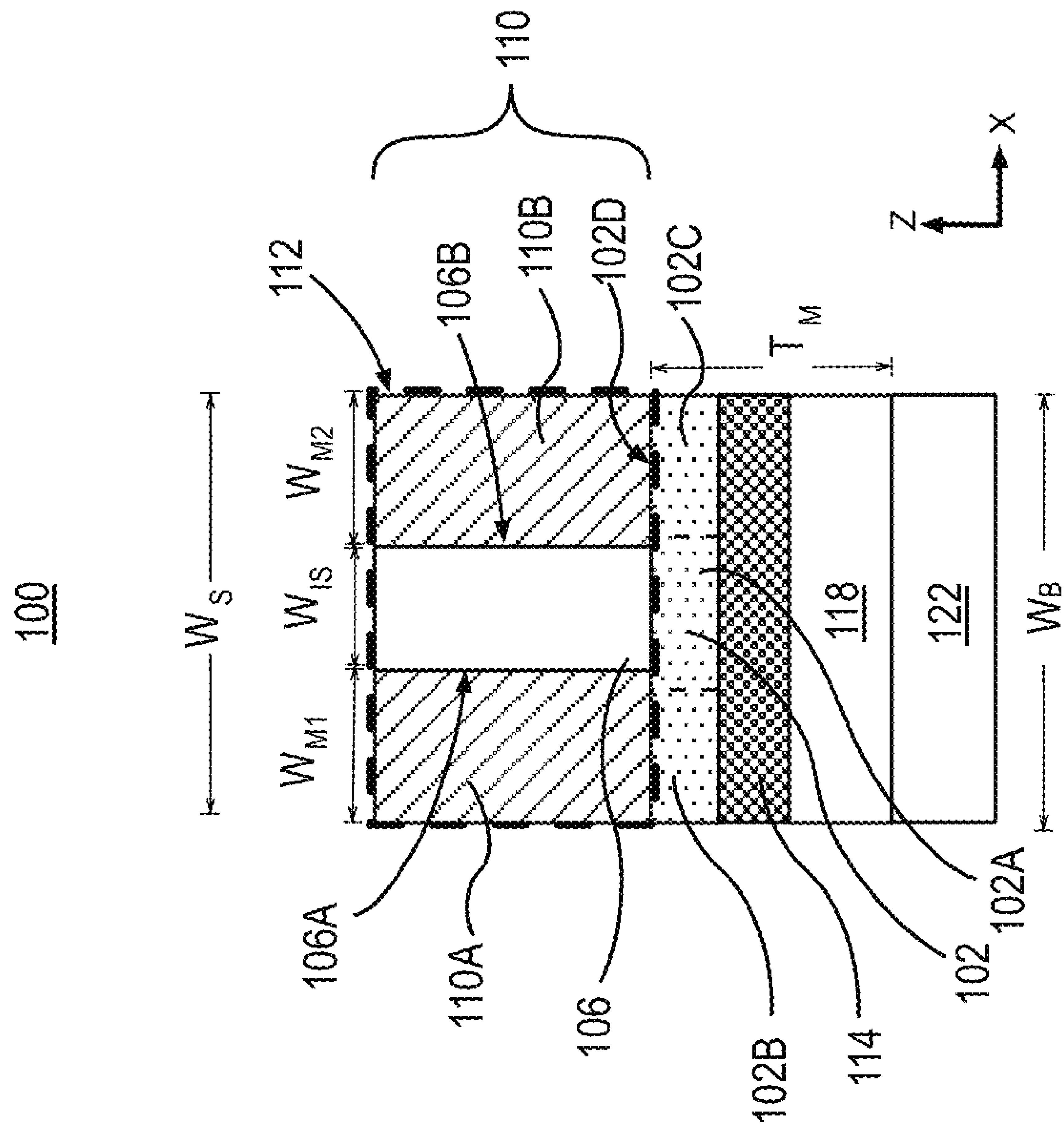


FIG. 1A

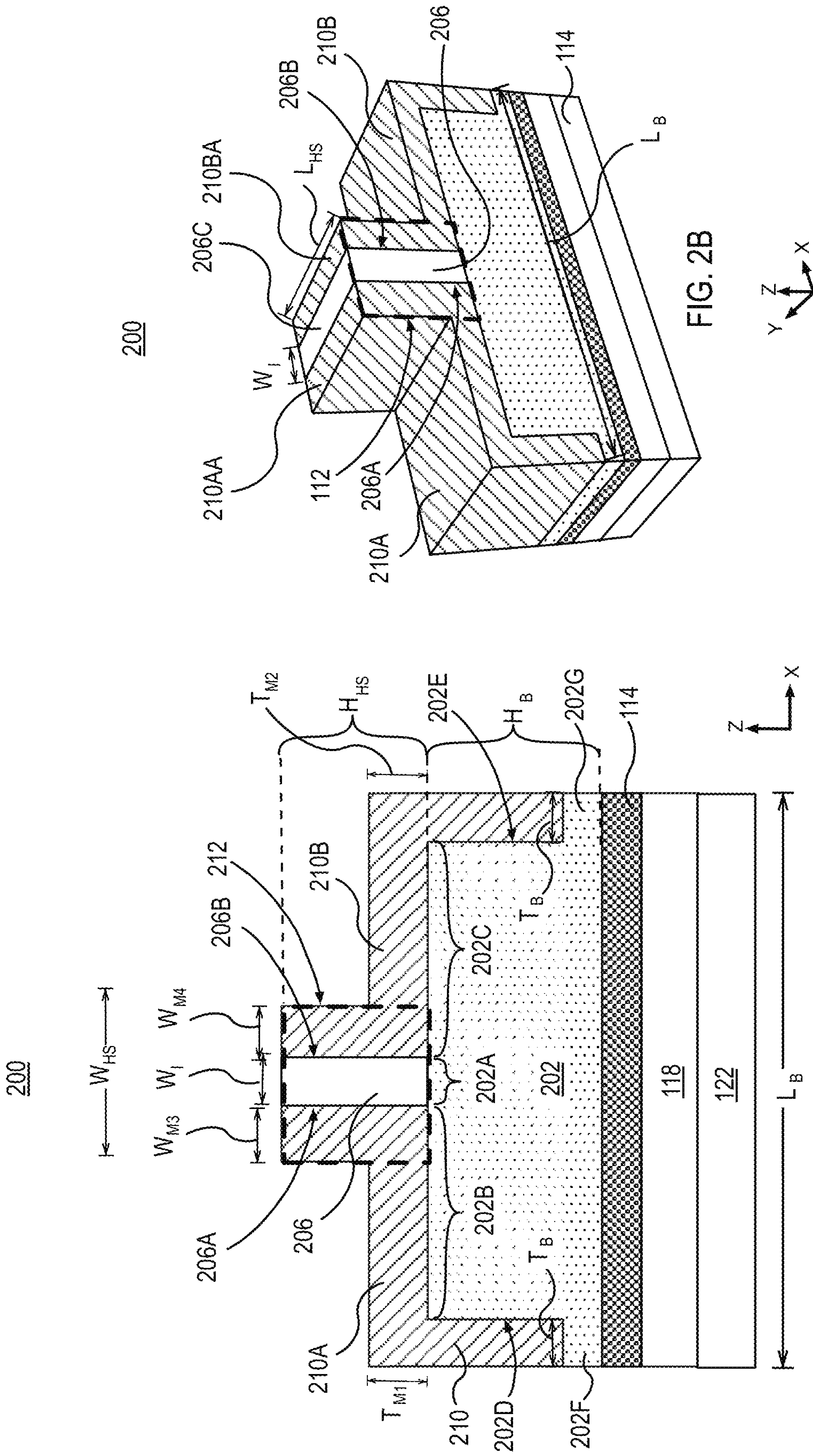


FIG. 2B

FIG. 2A

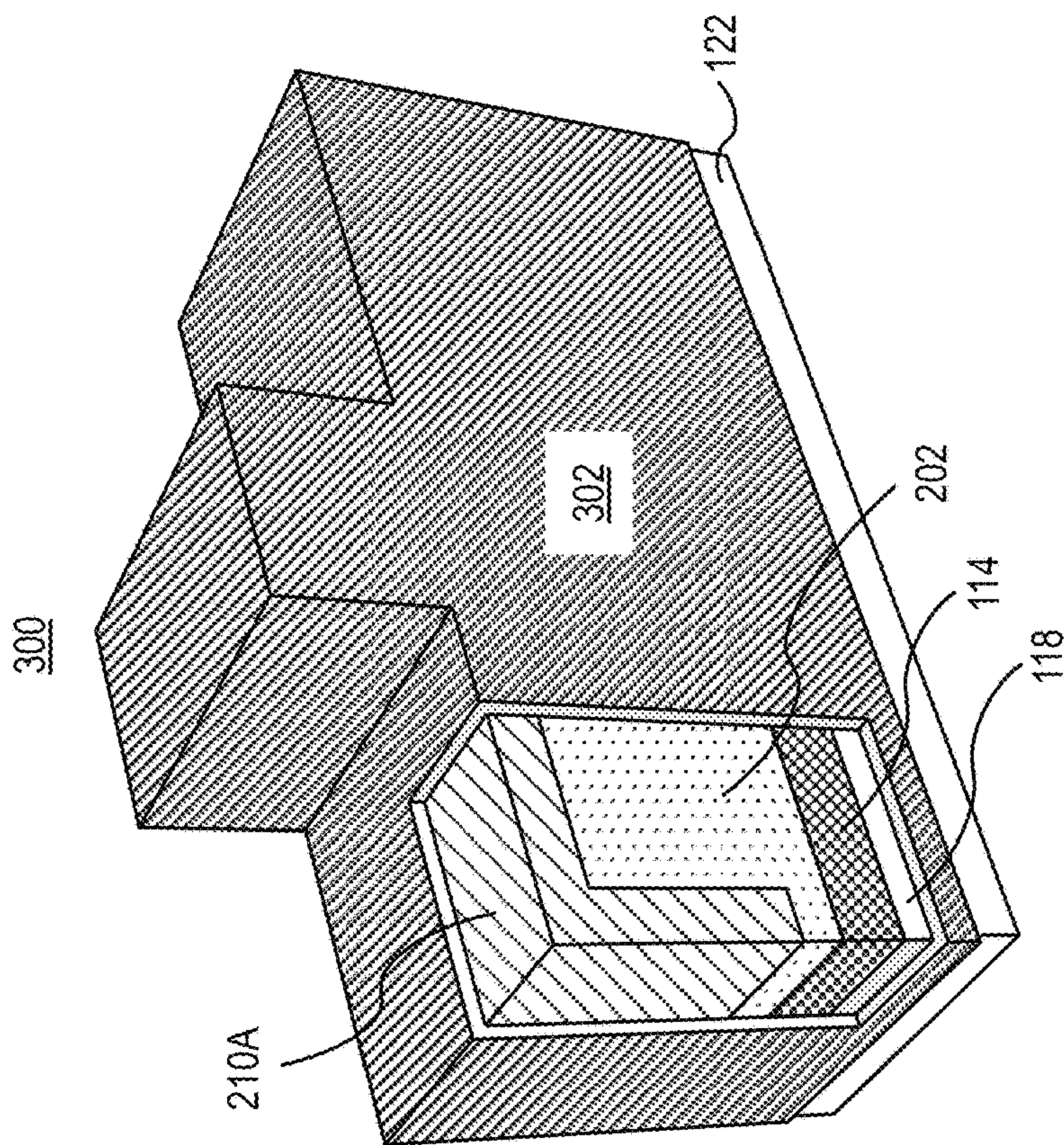
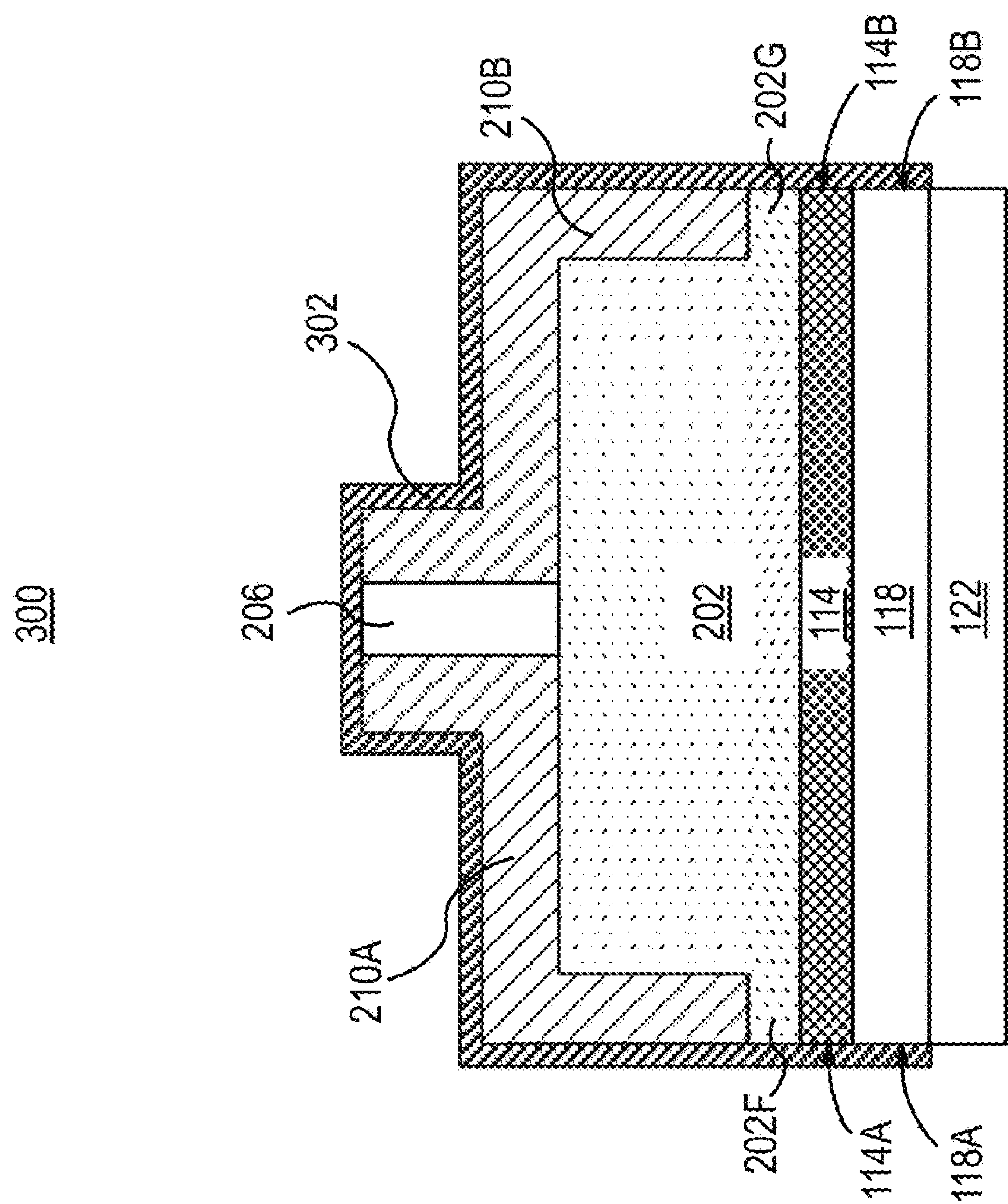


FIG. 3B



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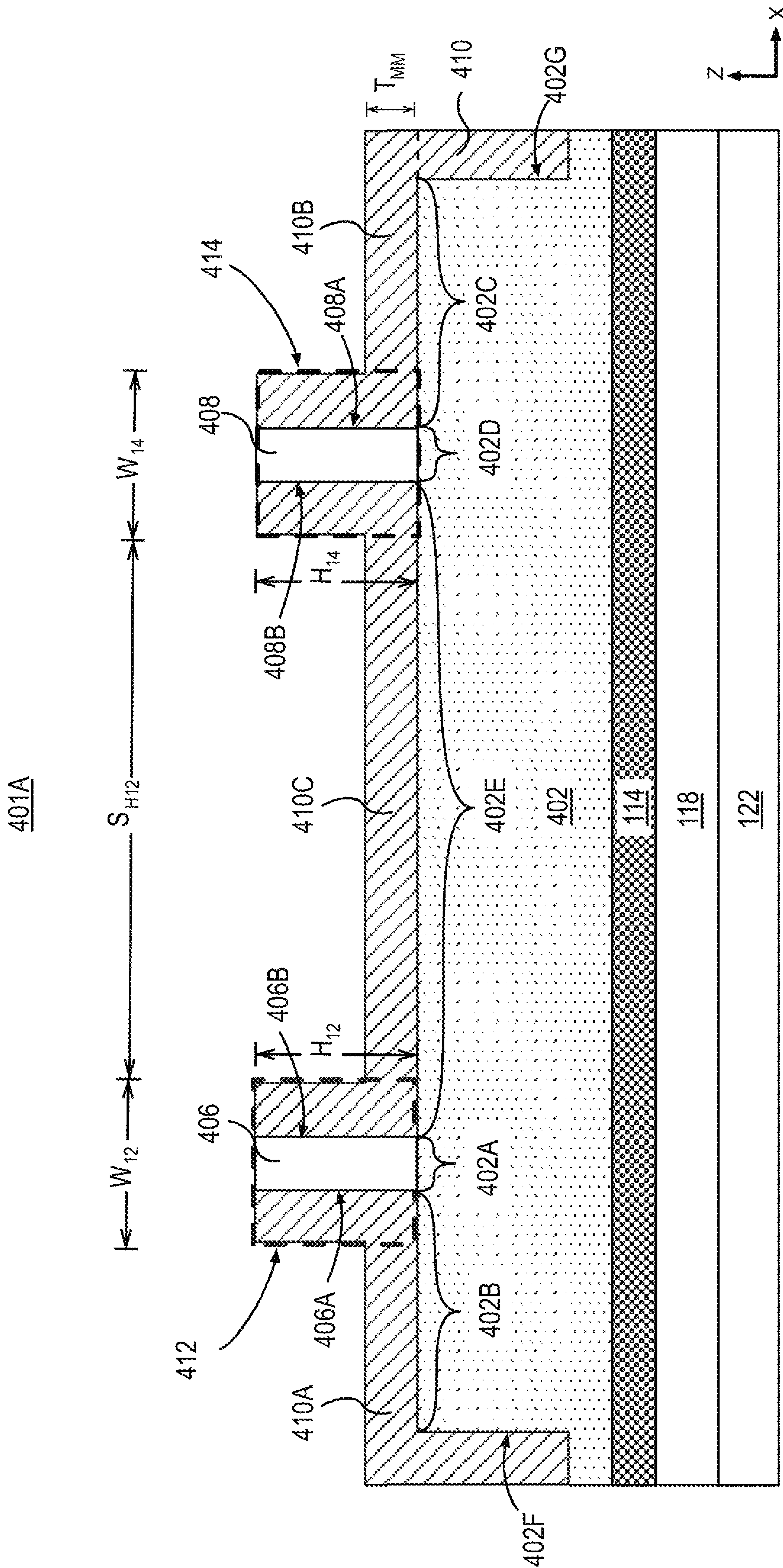


FIG. 4A

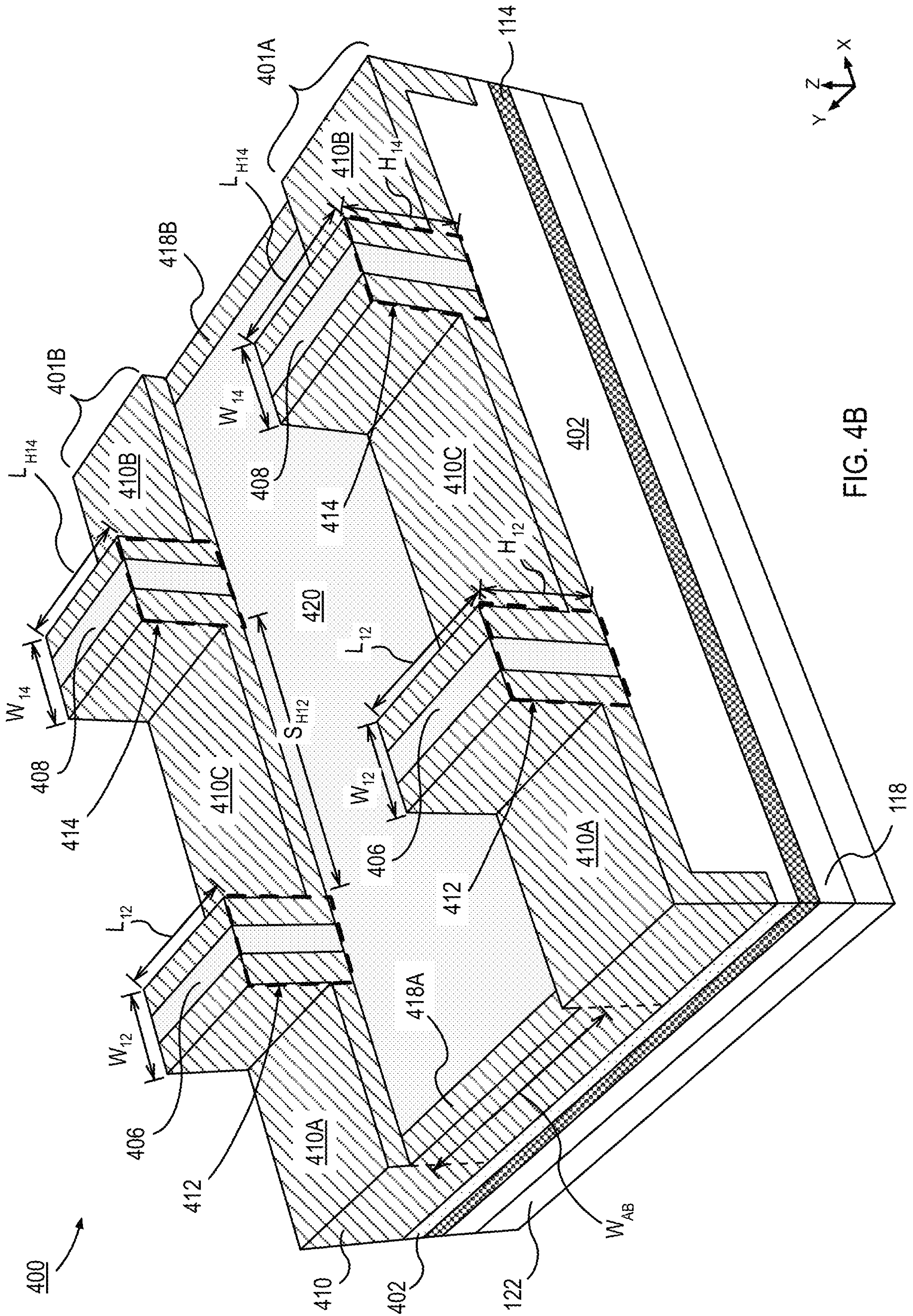


FIG. 4B

FIG. 4C

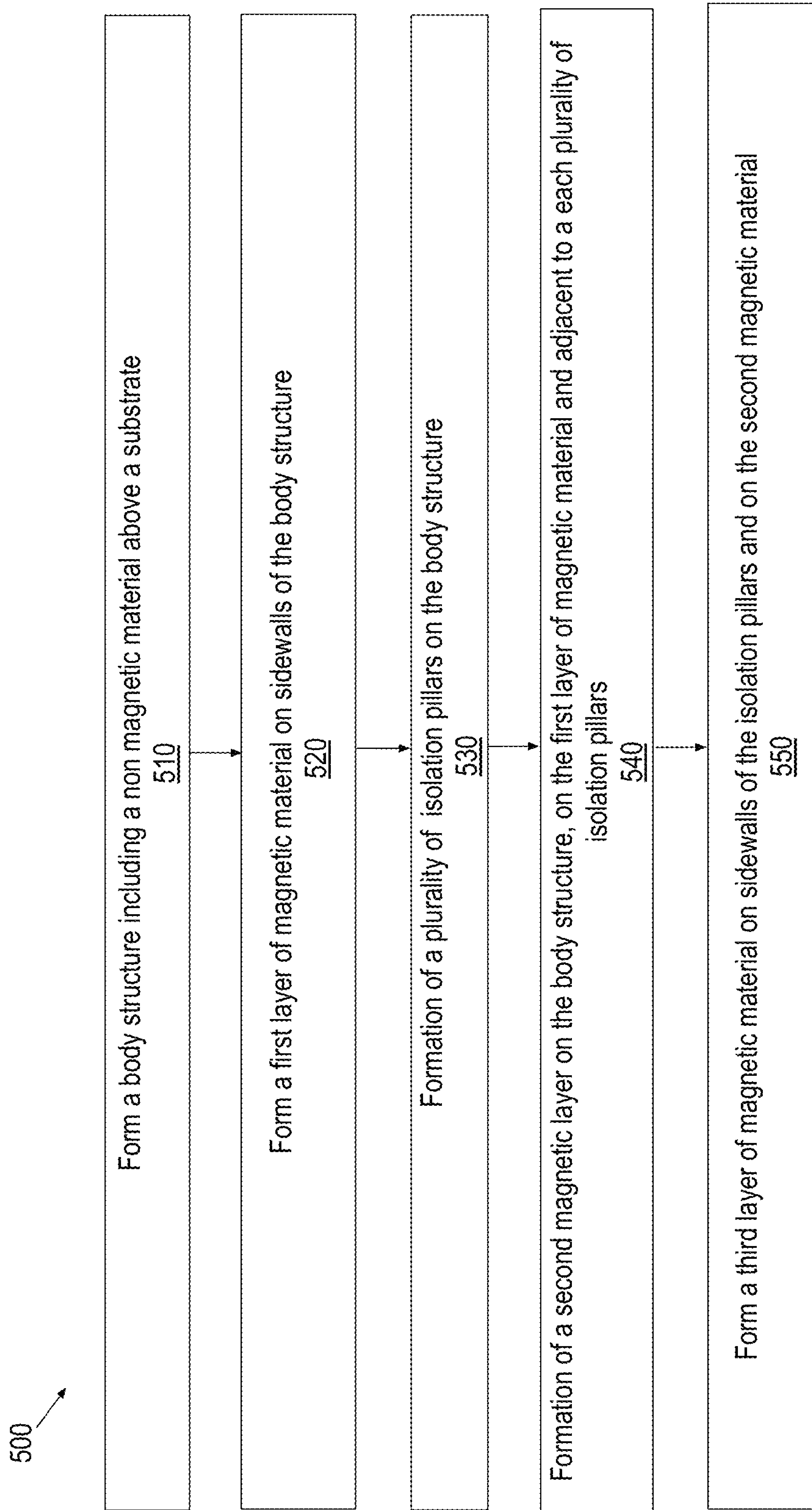


FIG. 5

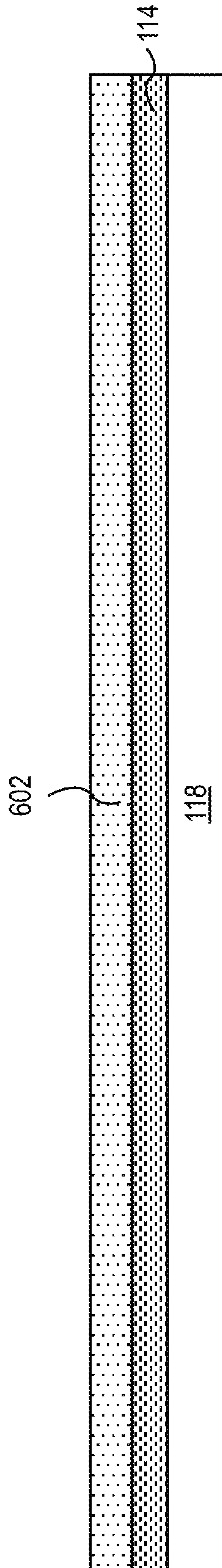


FIG. 6A

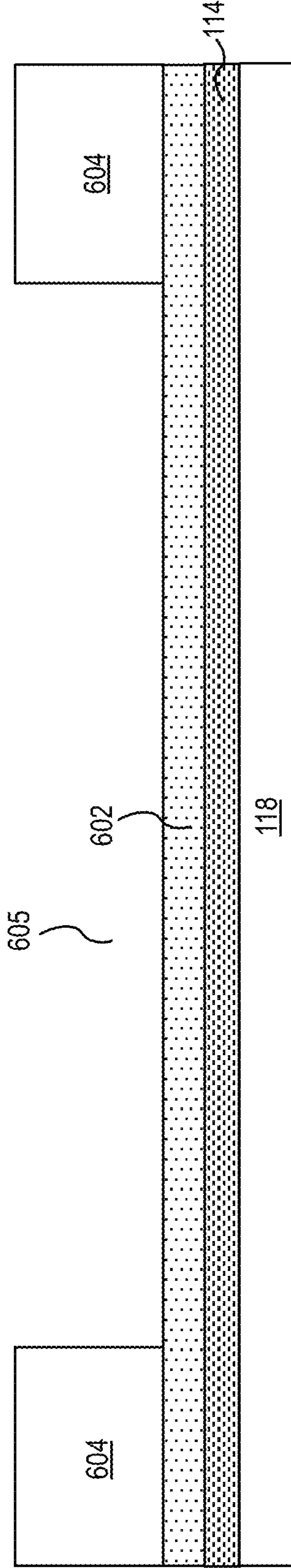
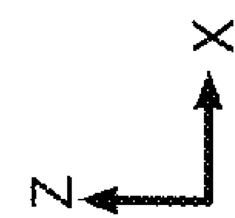
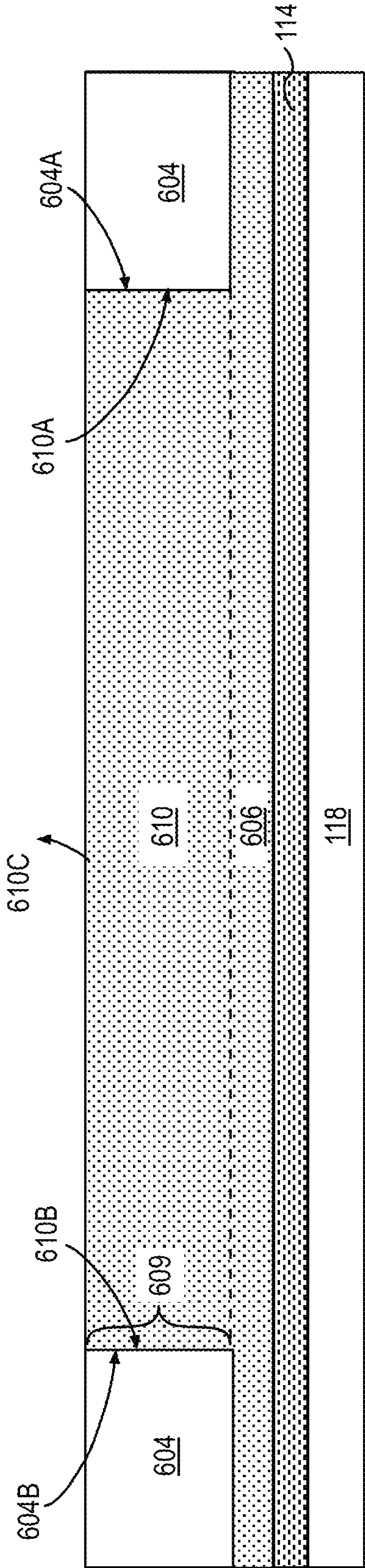


FIG. 6B





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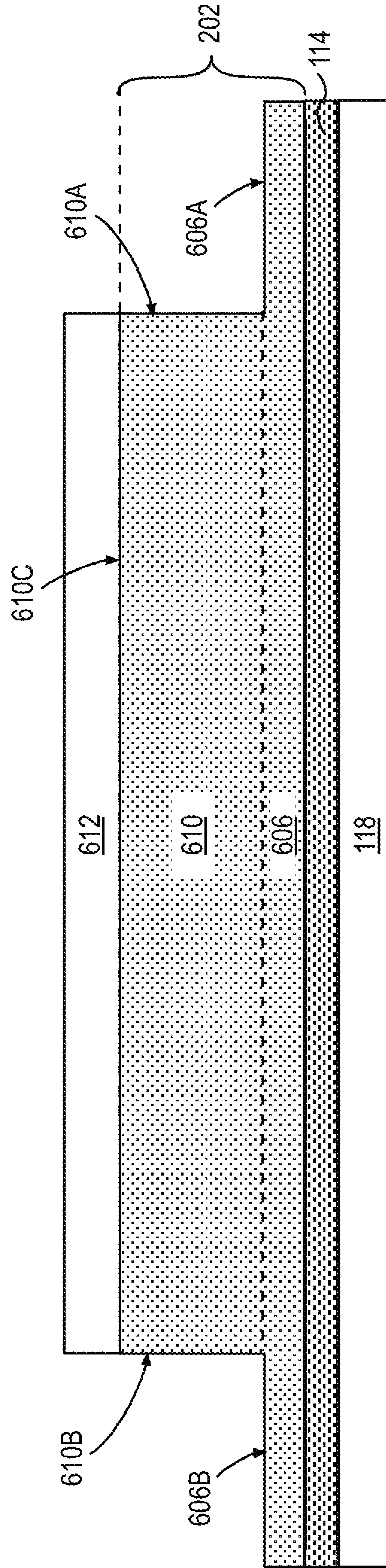
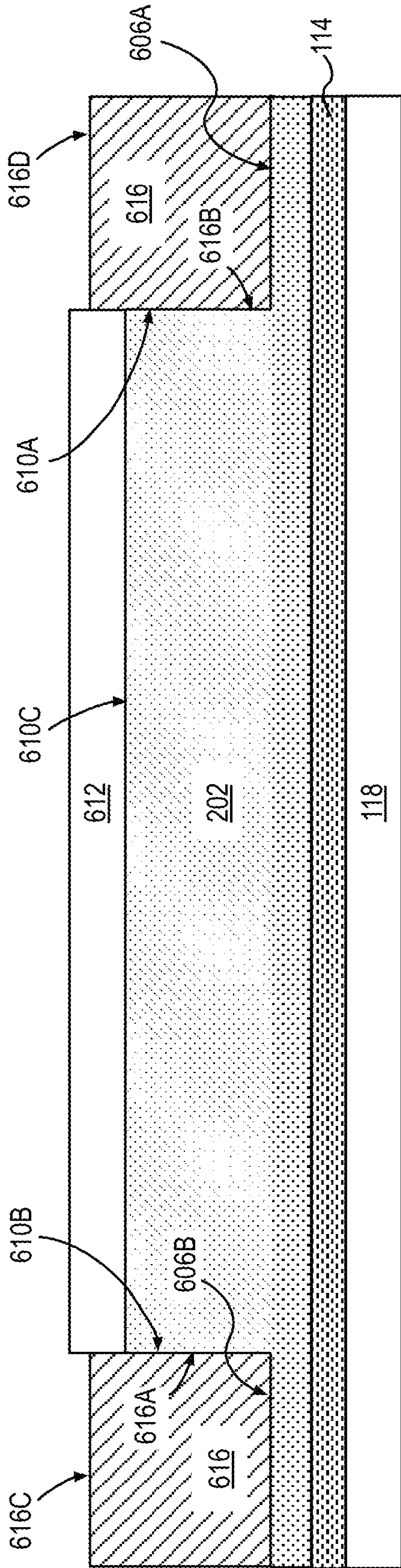


FIG. 6D



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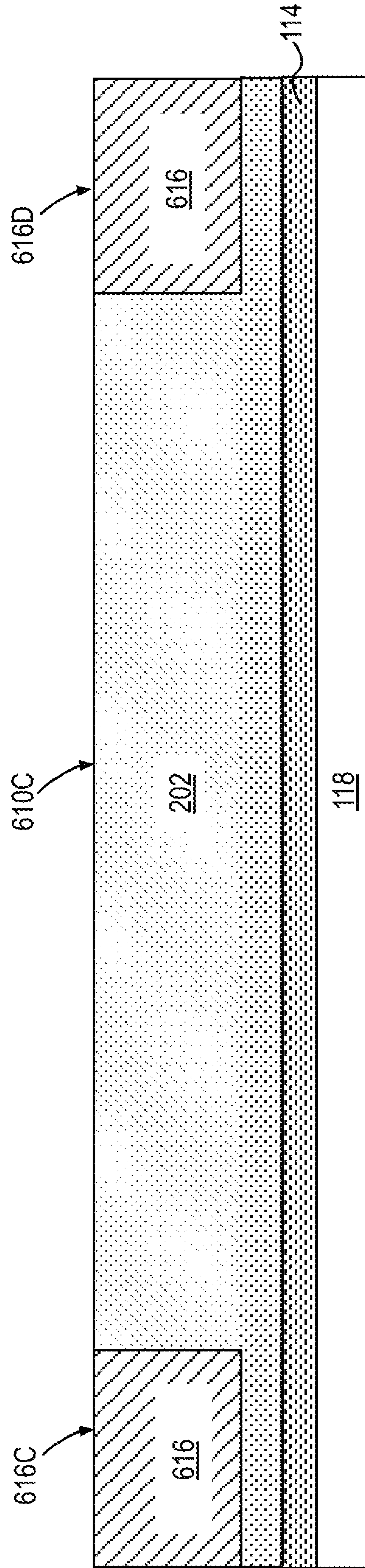
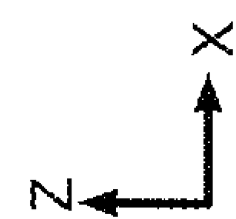


FIG. 6F



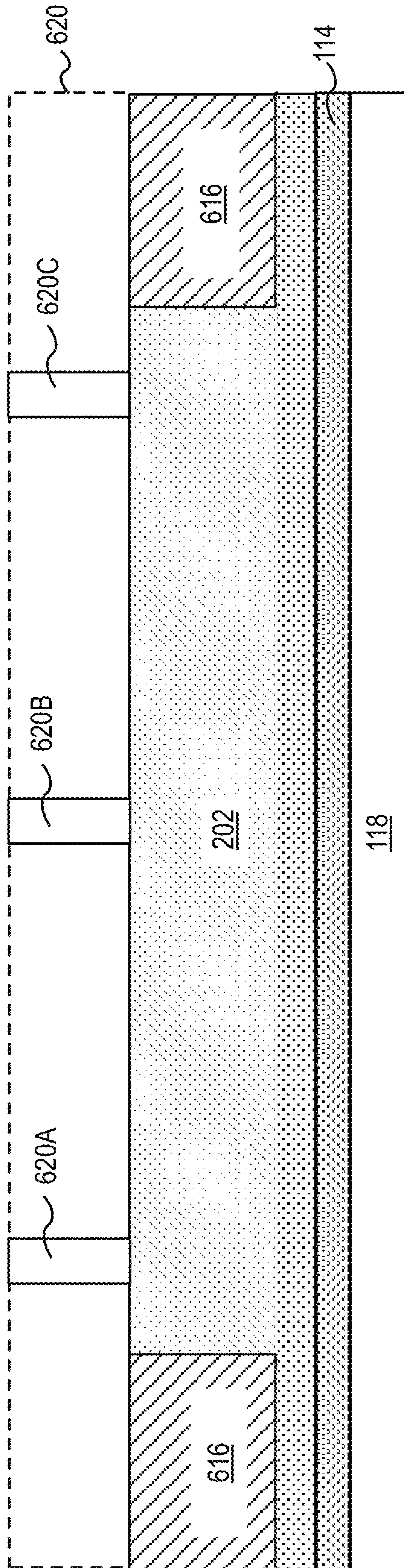


FIG. 6G

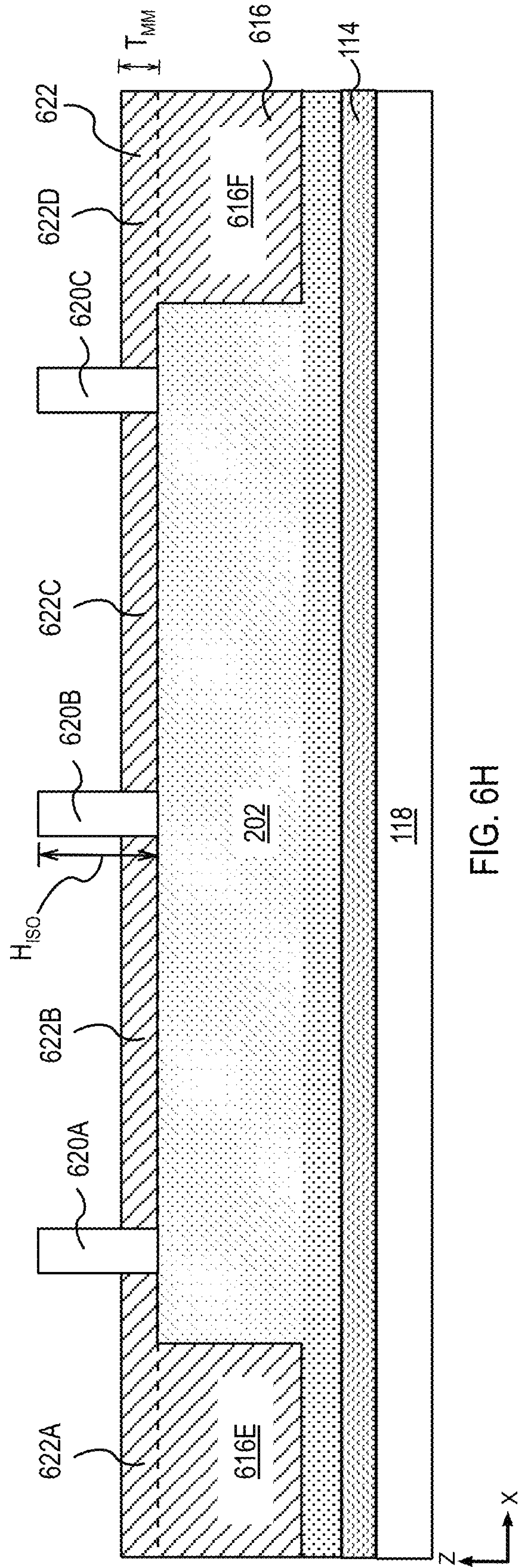


FIG. 6H

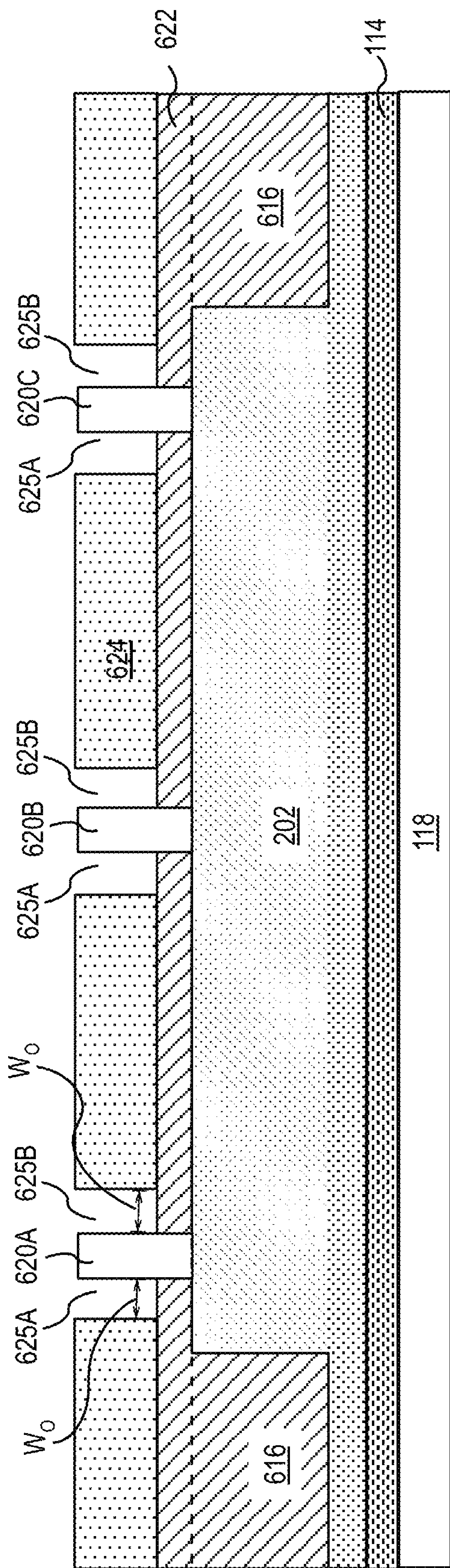


FIG. 6I

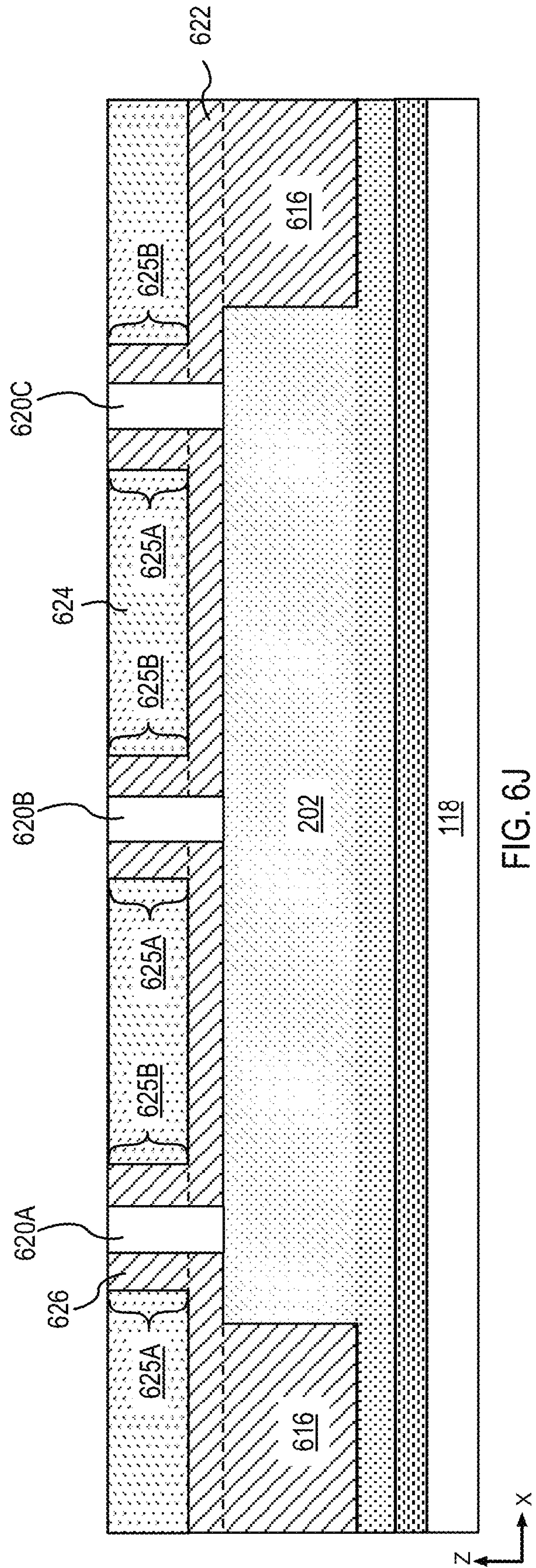


FIG. 6J

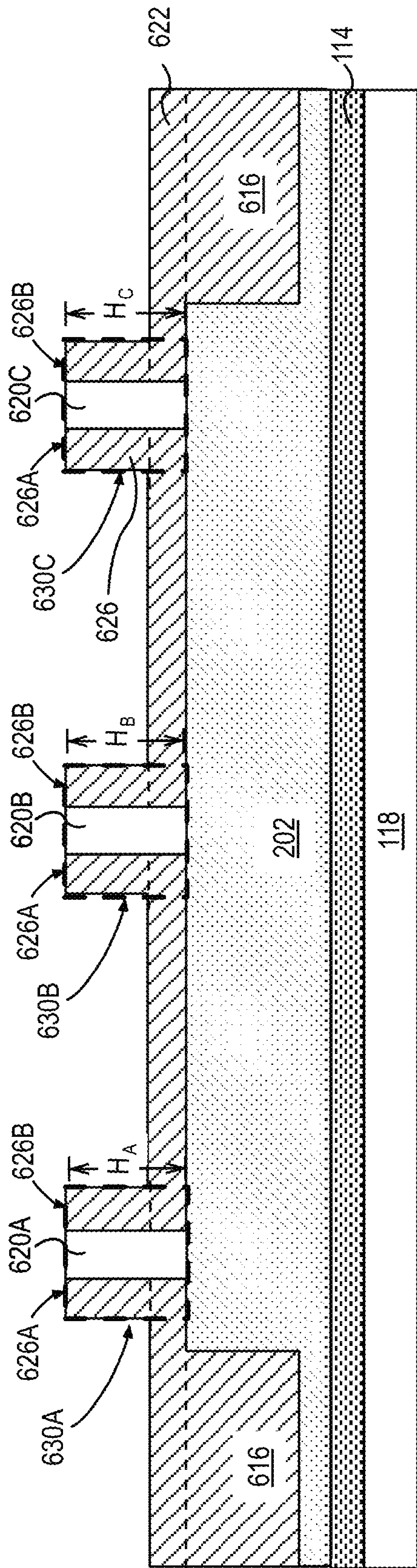


FIG. 6K

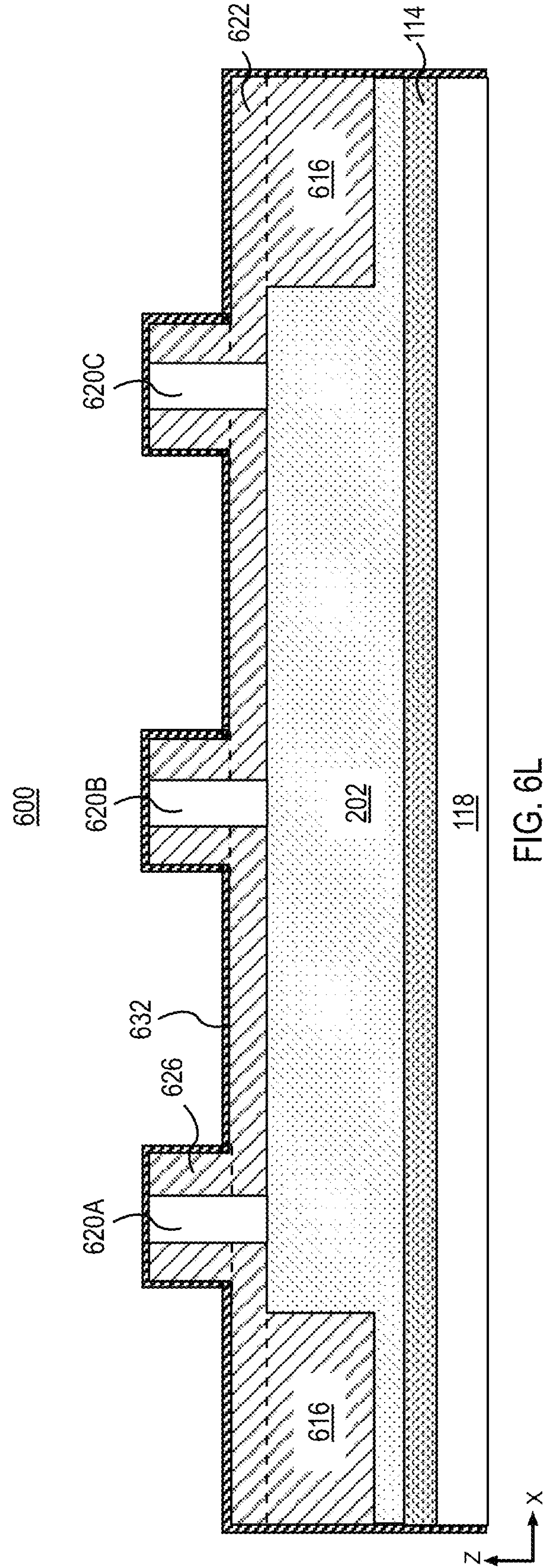
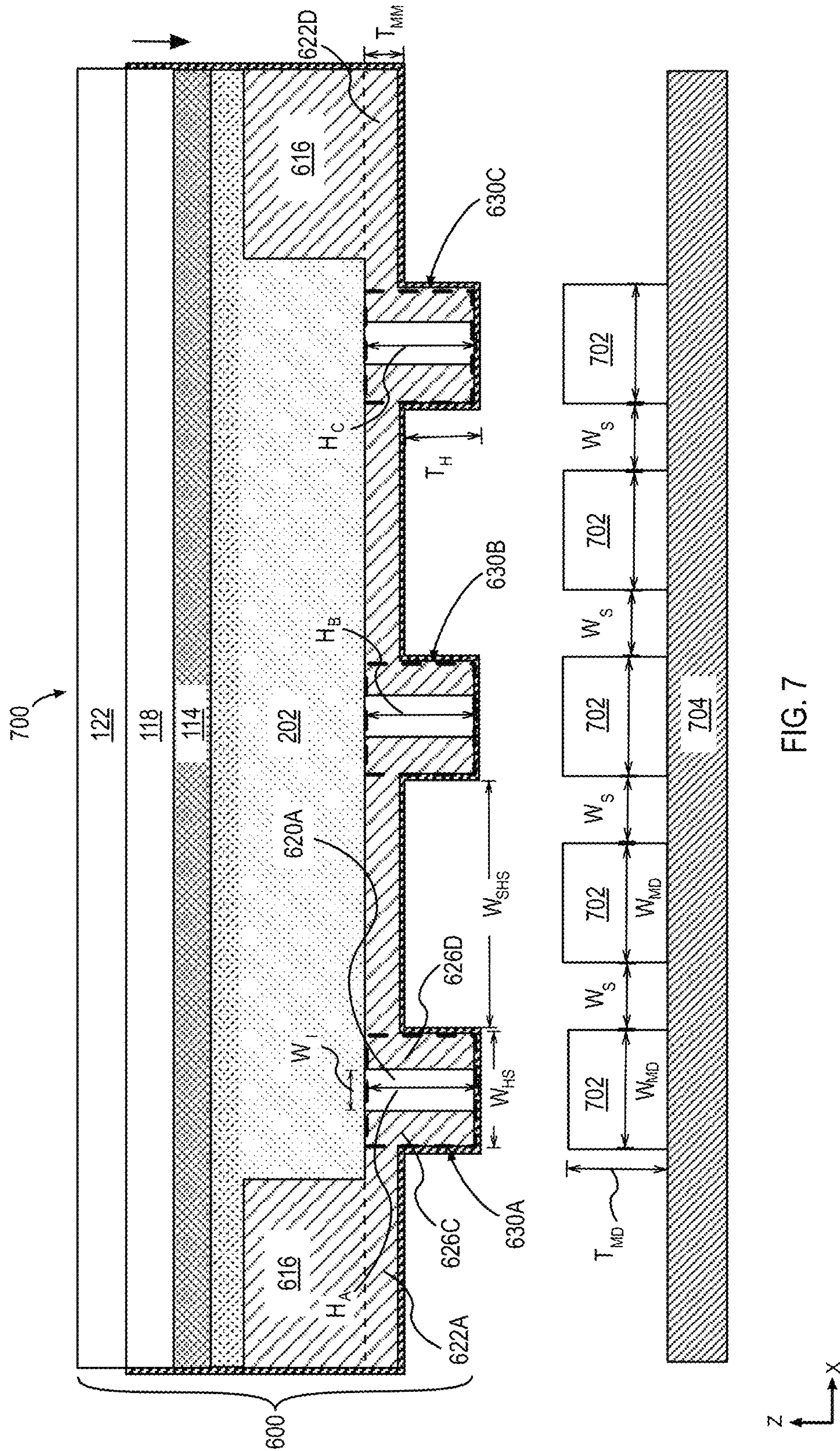


FIG. 6L


700
122
118
114
202
616
616
622D
622A
620A
626C
626D
630A
630B
630C
702
702
702
702
702
704
FIG. 7
600
Z
X

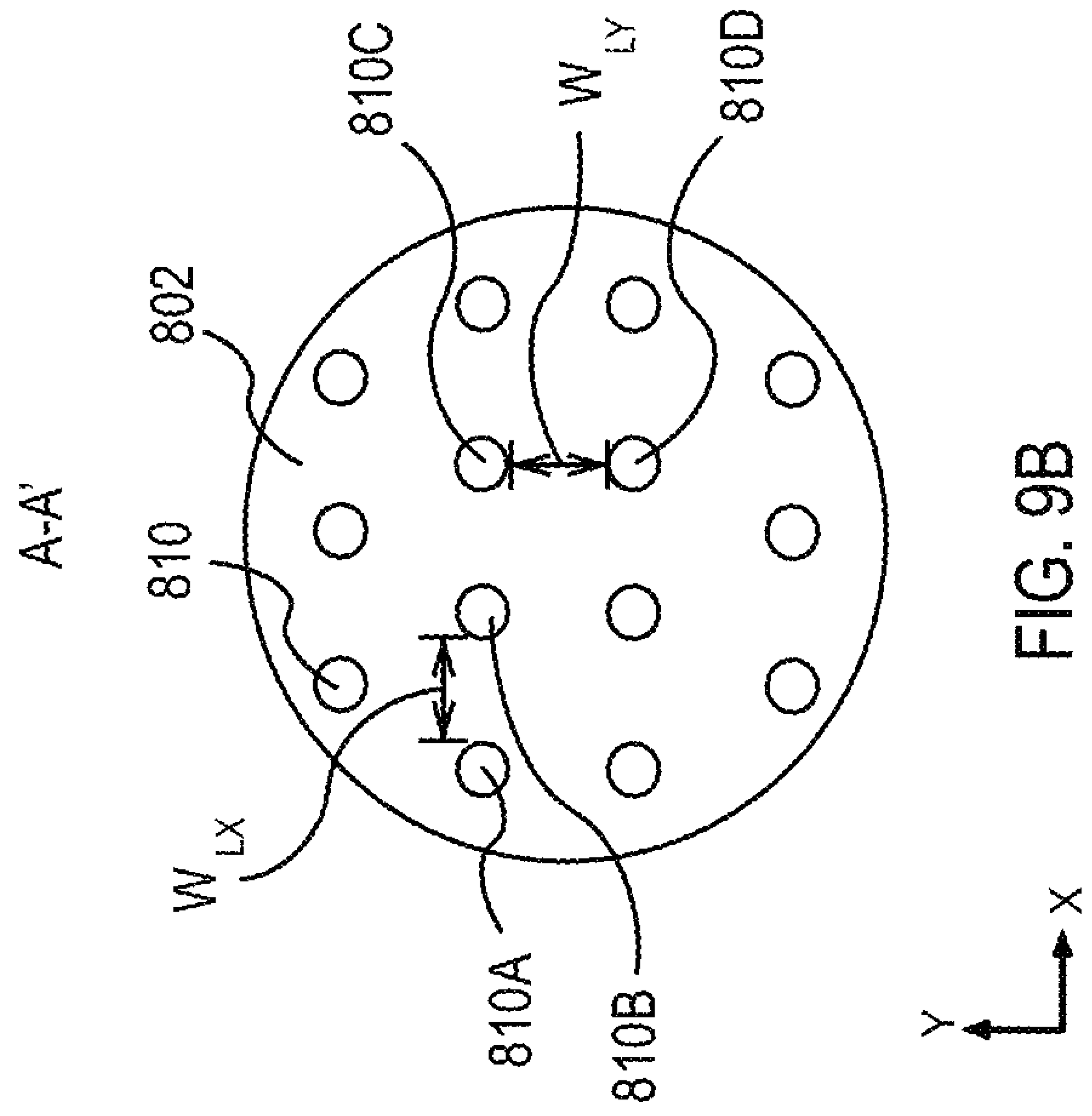


FIG. 9B

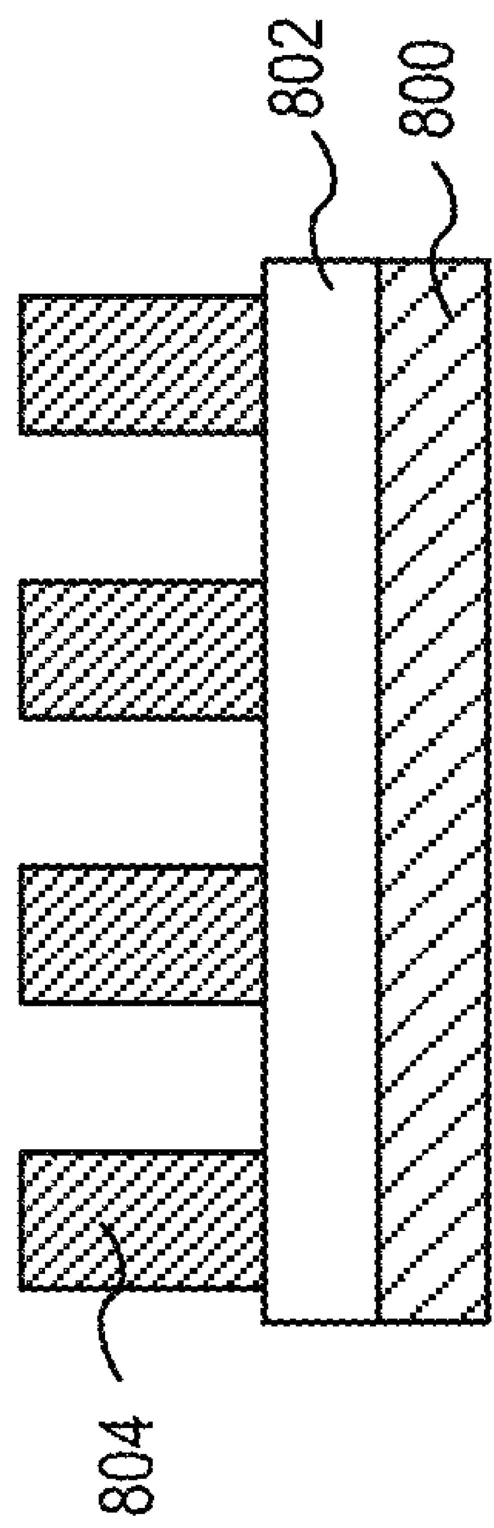


FIG. 8

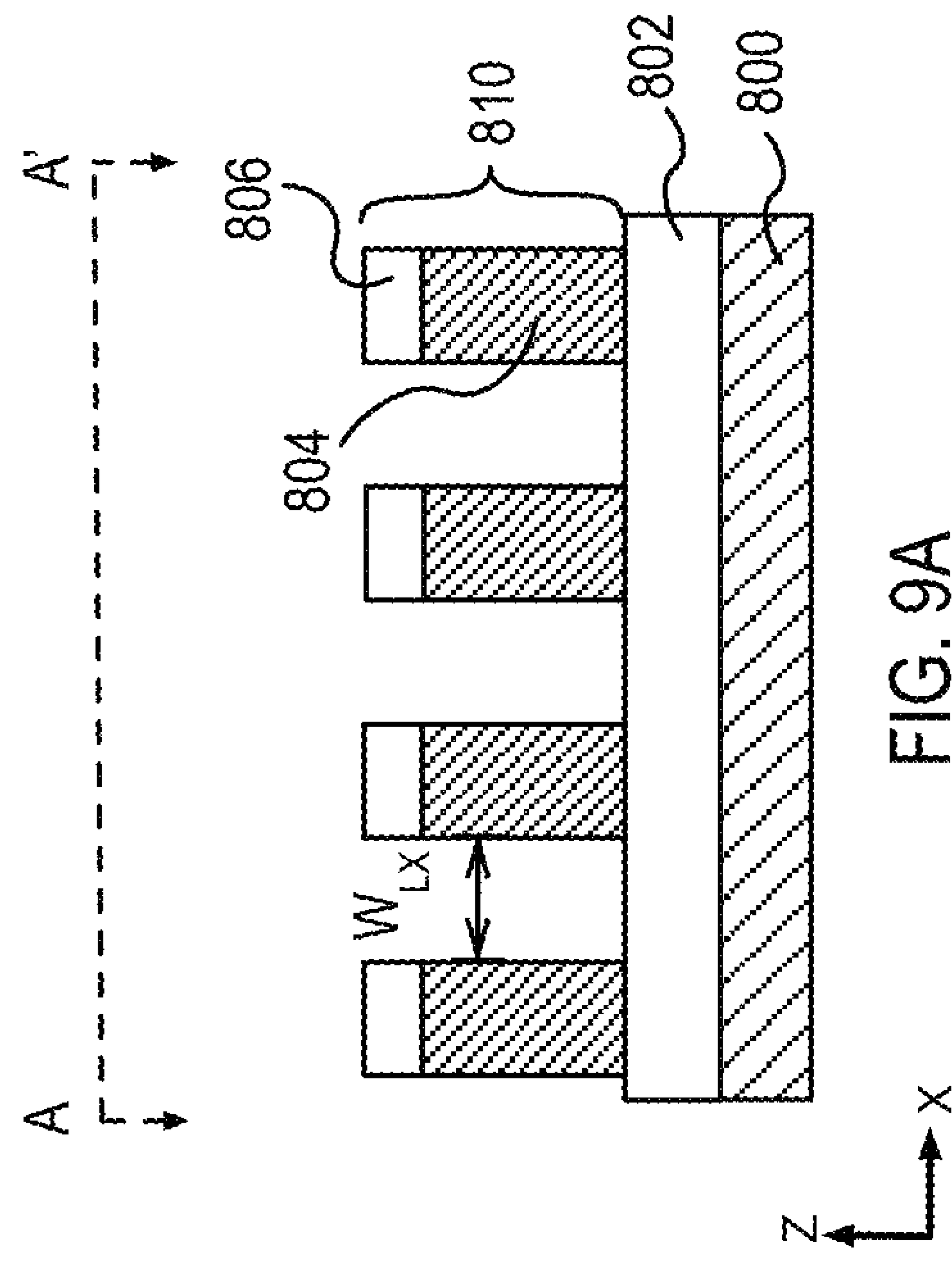


FIG. 9A

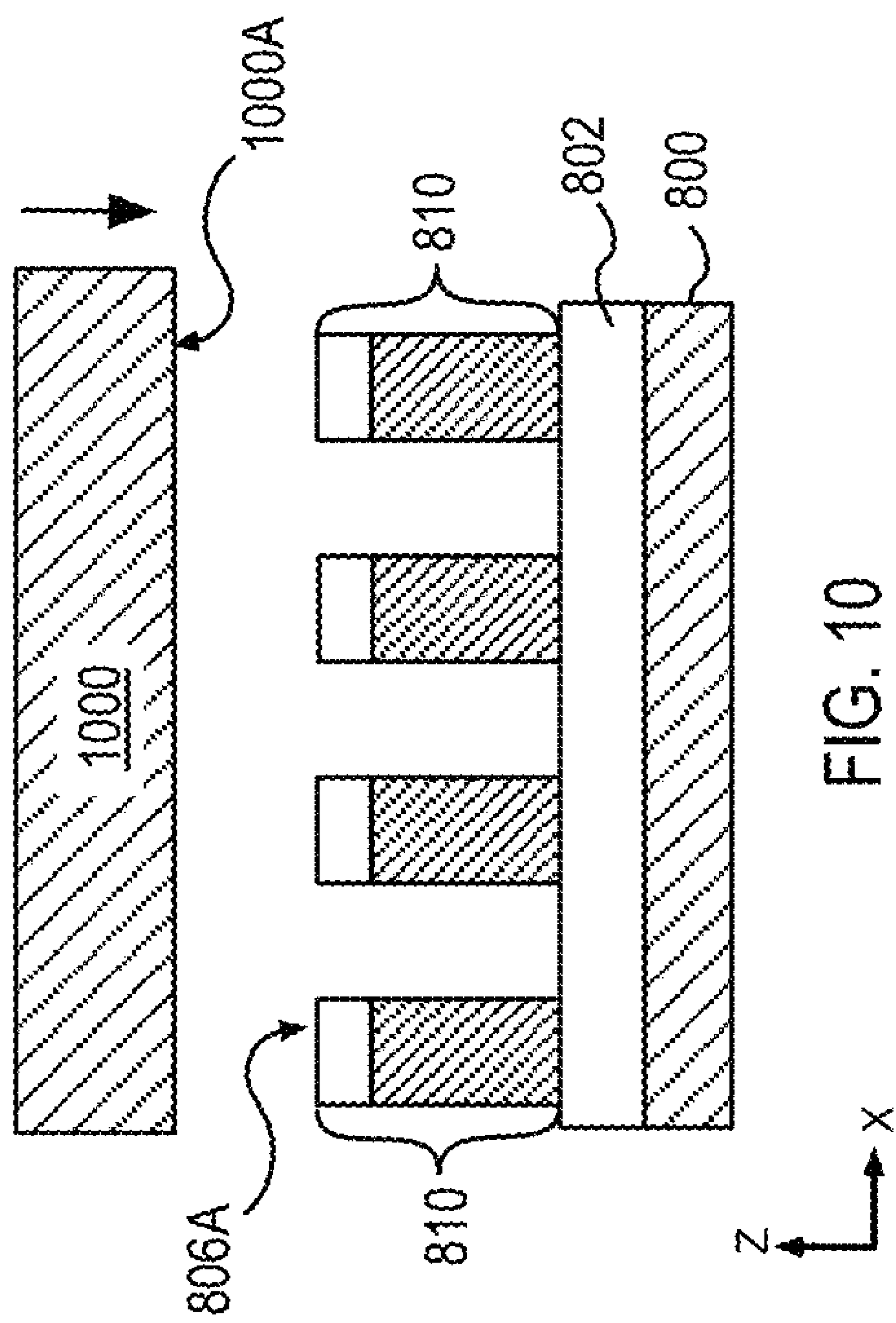


FIG. 10

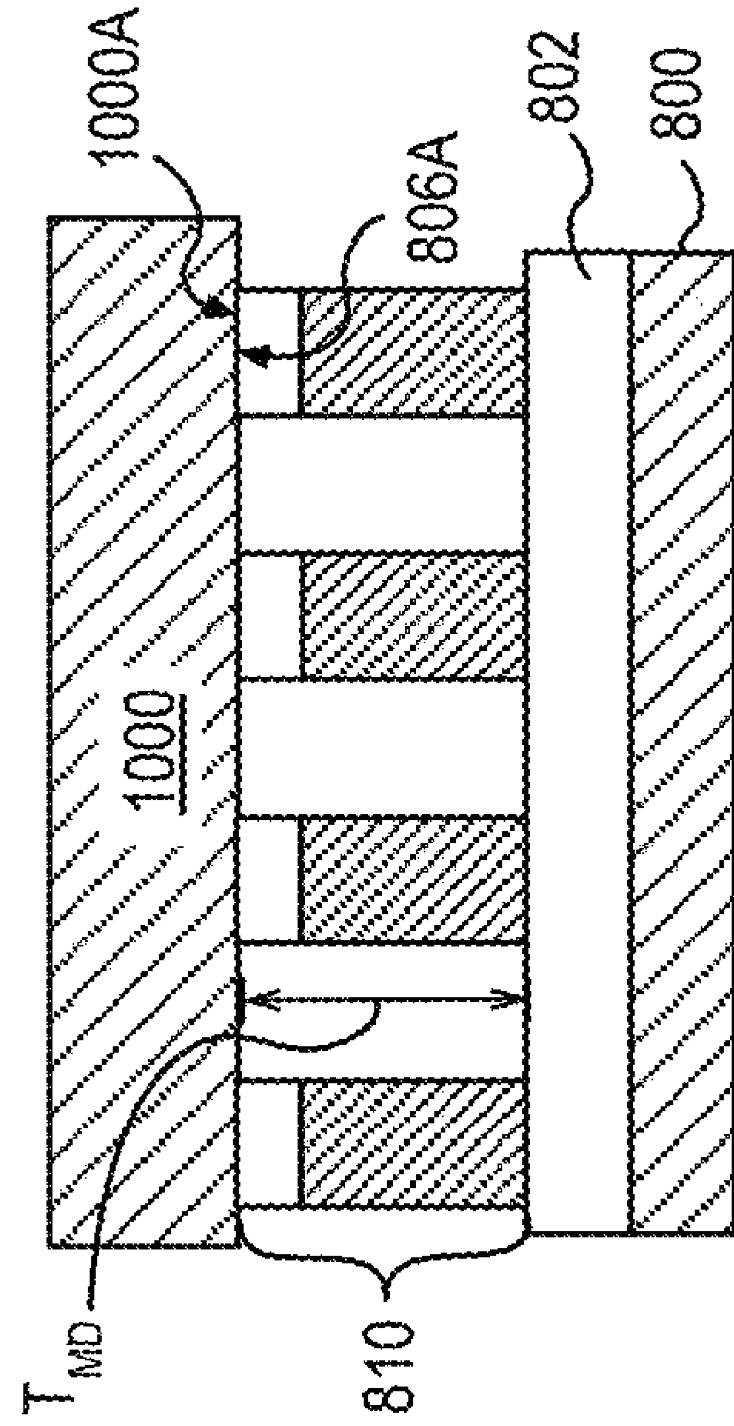


FIG. 11

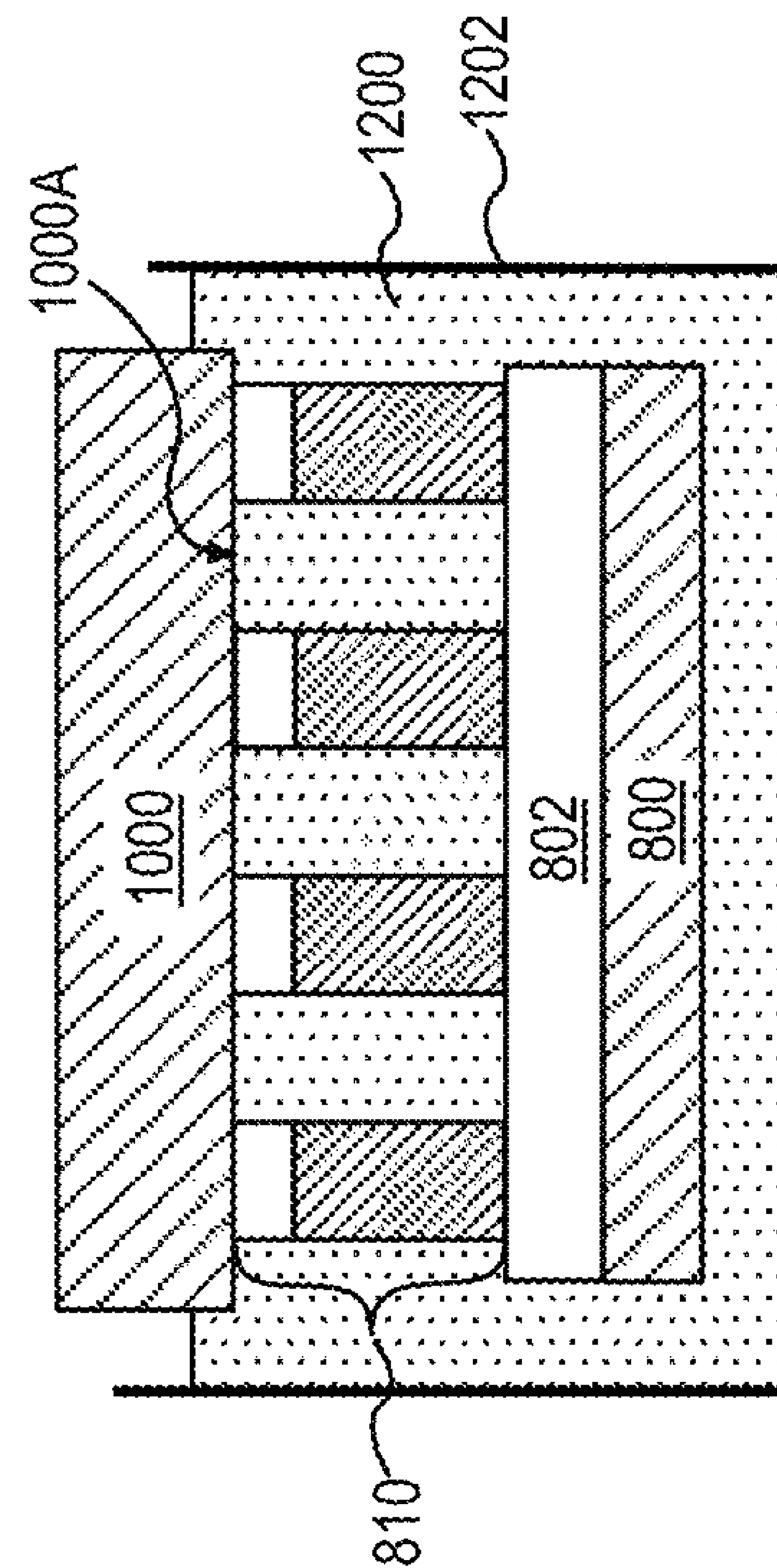


FIG. 12A

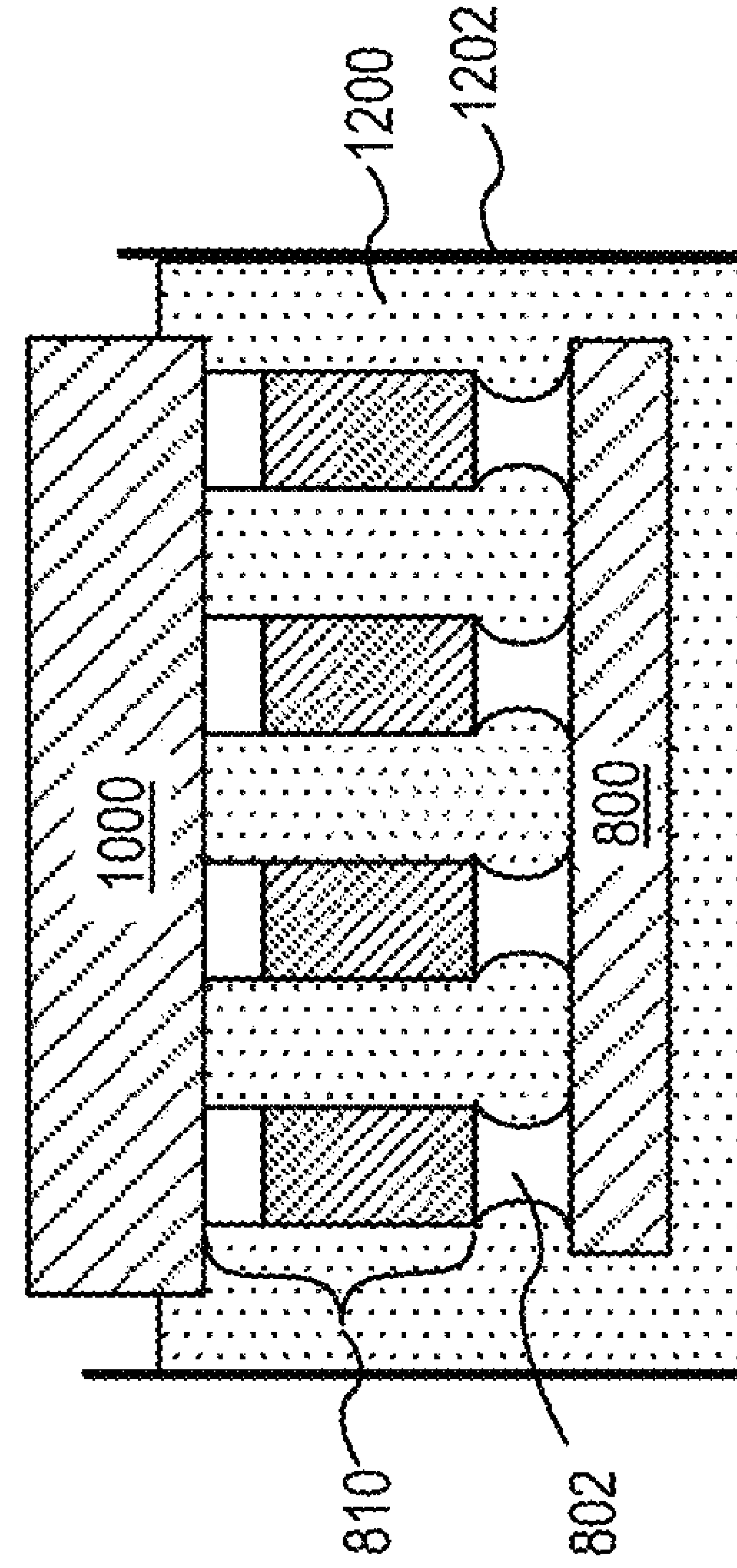


FIG. 12B

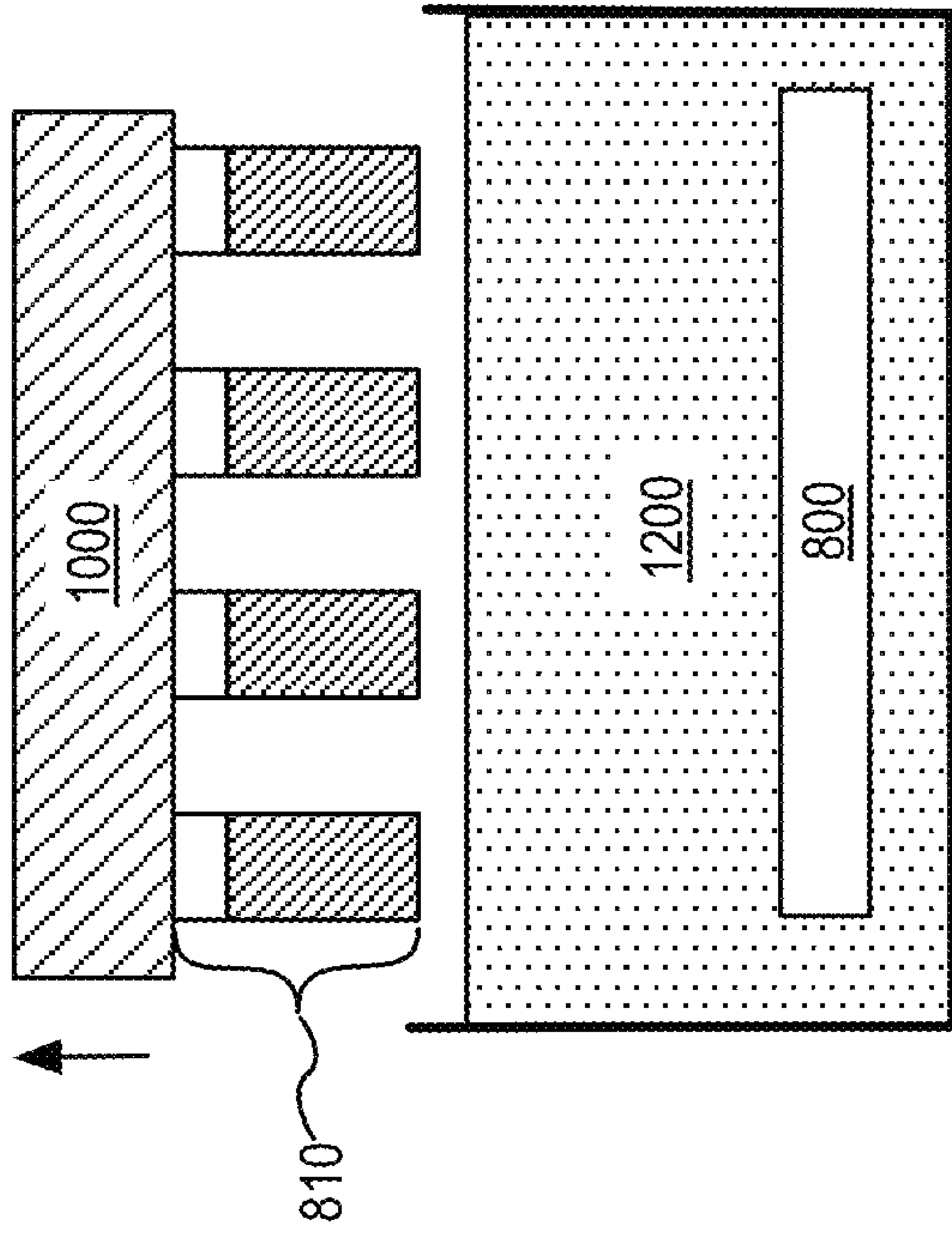


FIG. 12D

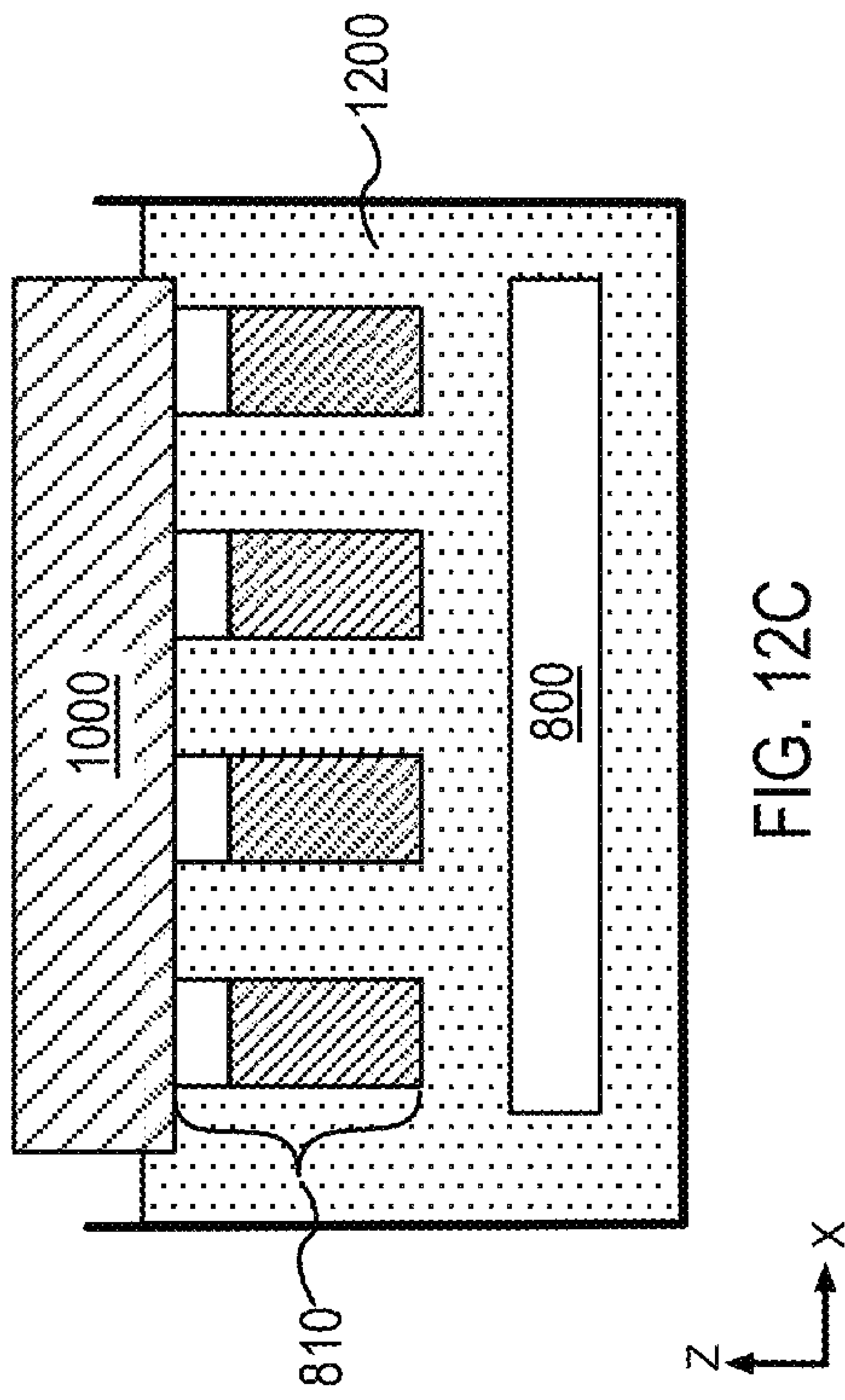


FIG. 12C

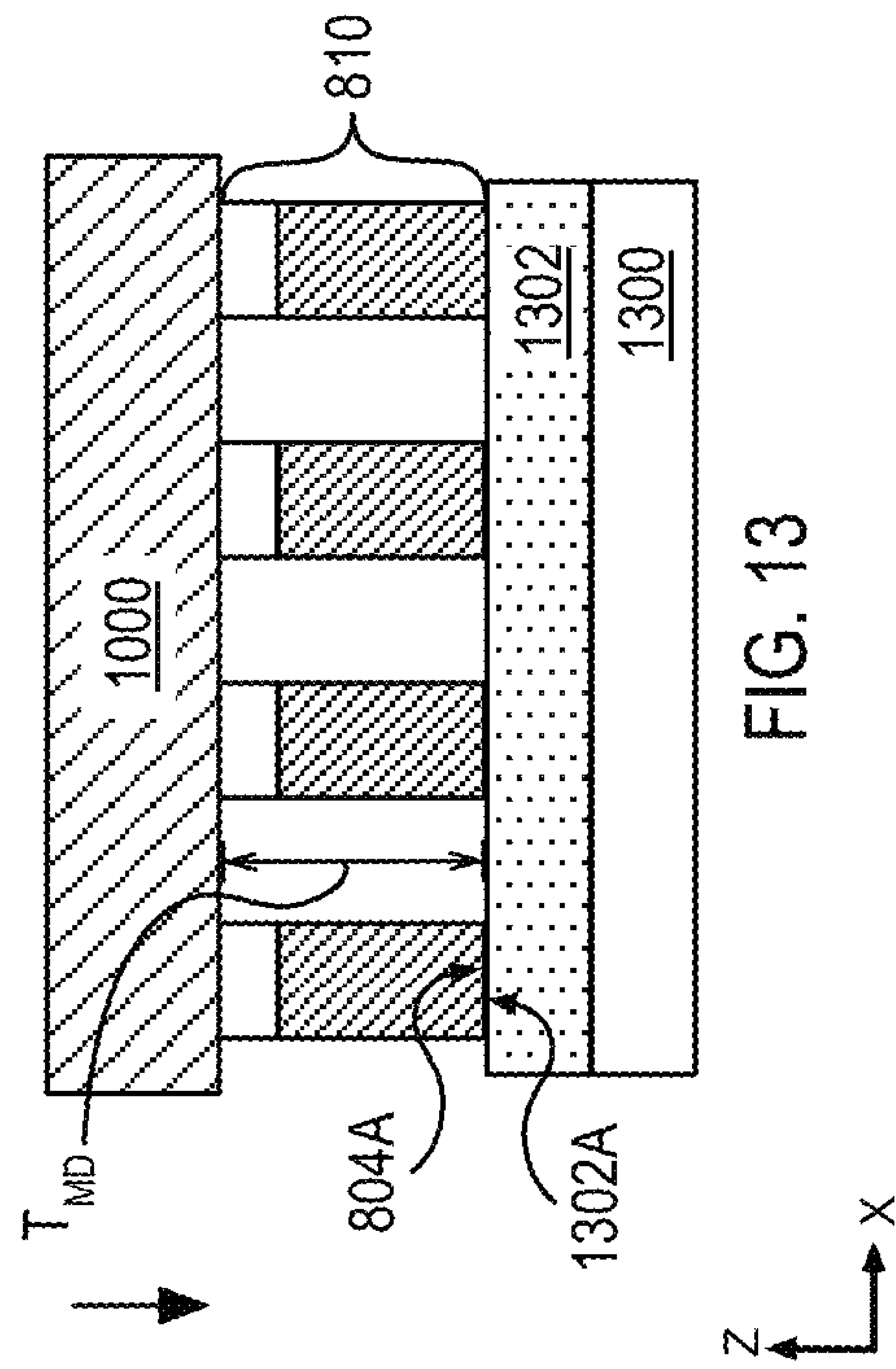


FIG. 13

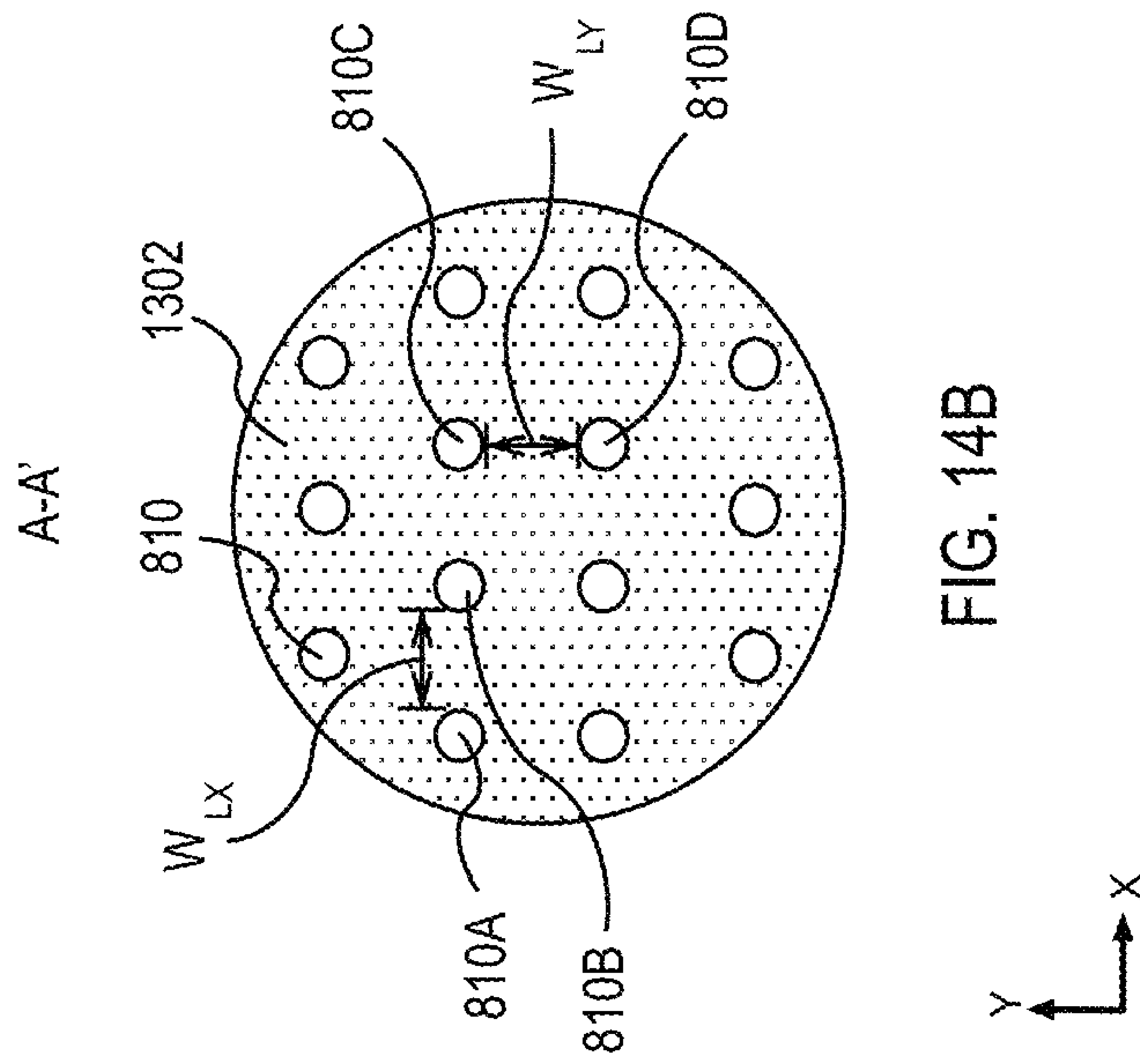


FIG. 14B

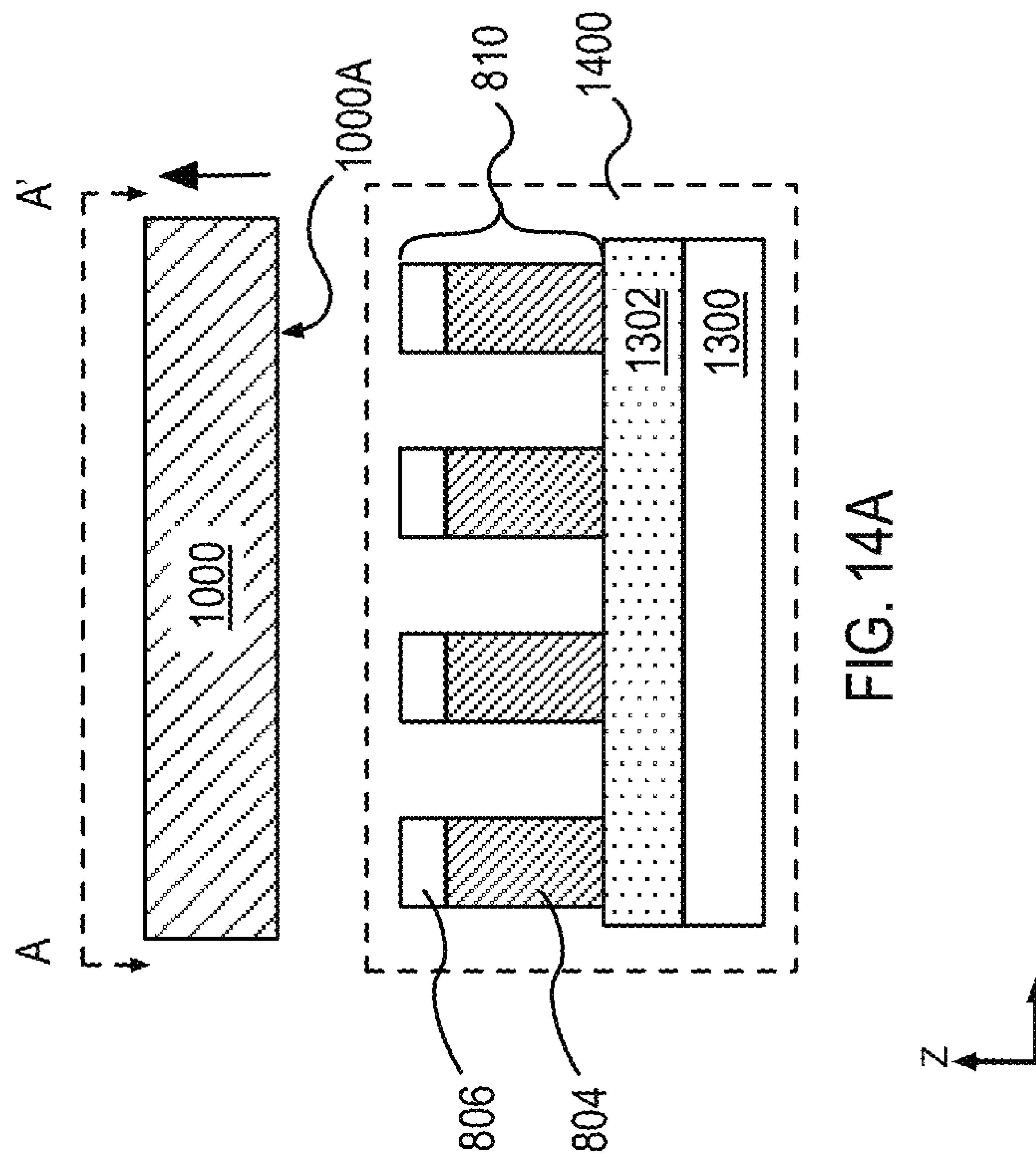


FIG. 14A

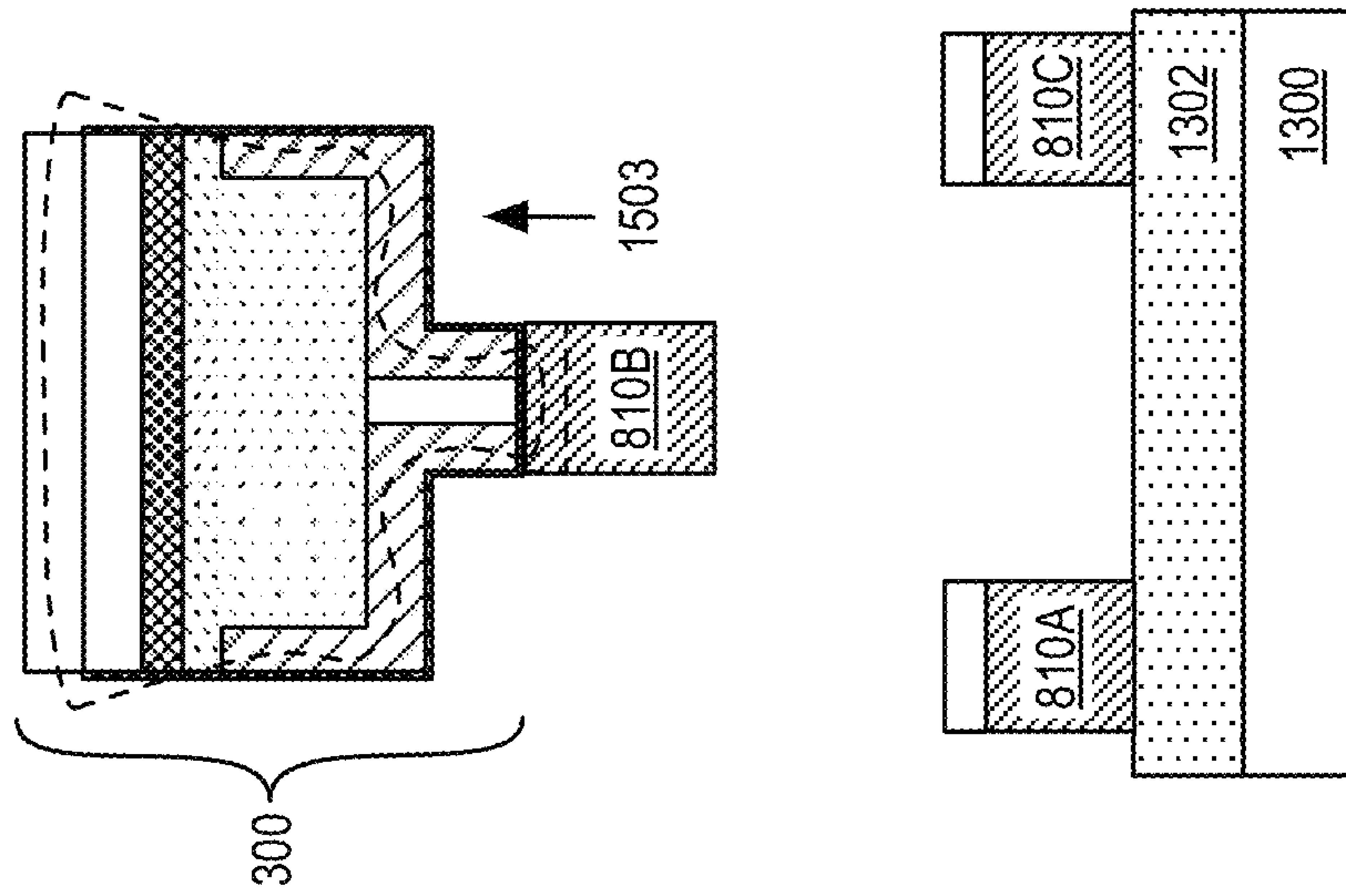


FIG. 15C

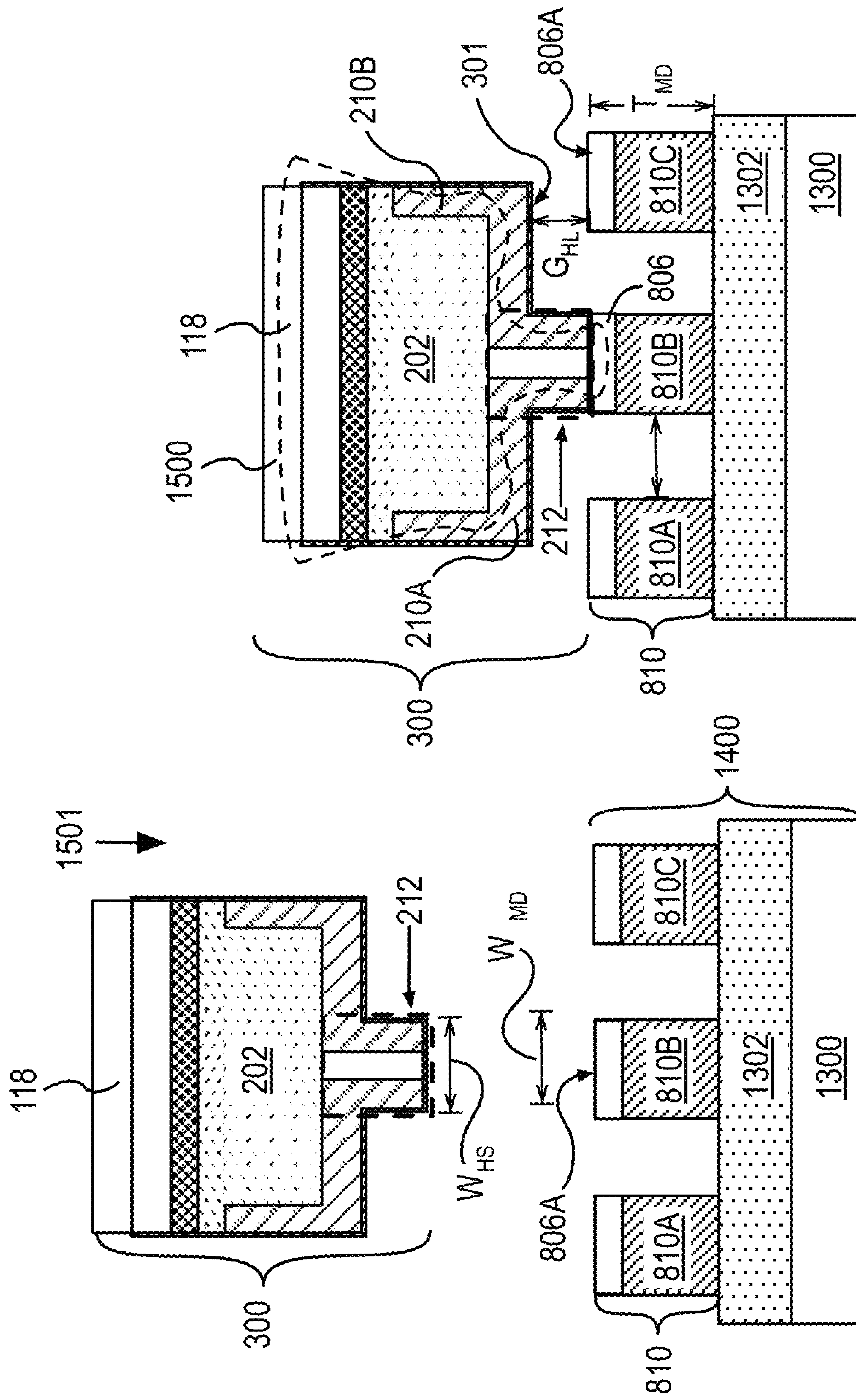


FIG. 15B

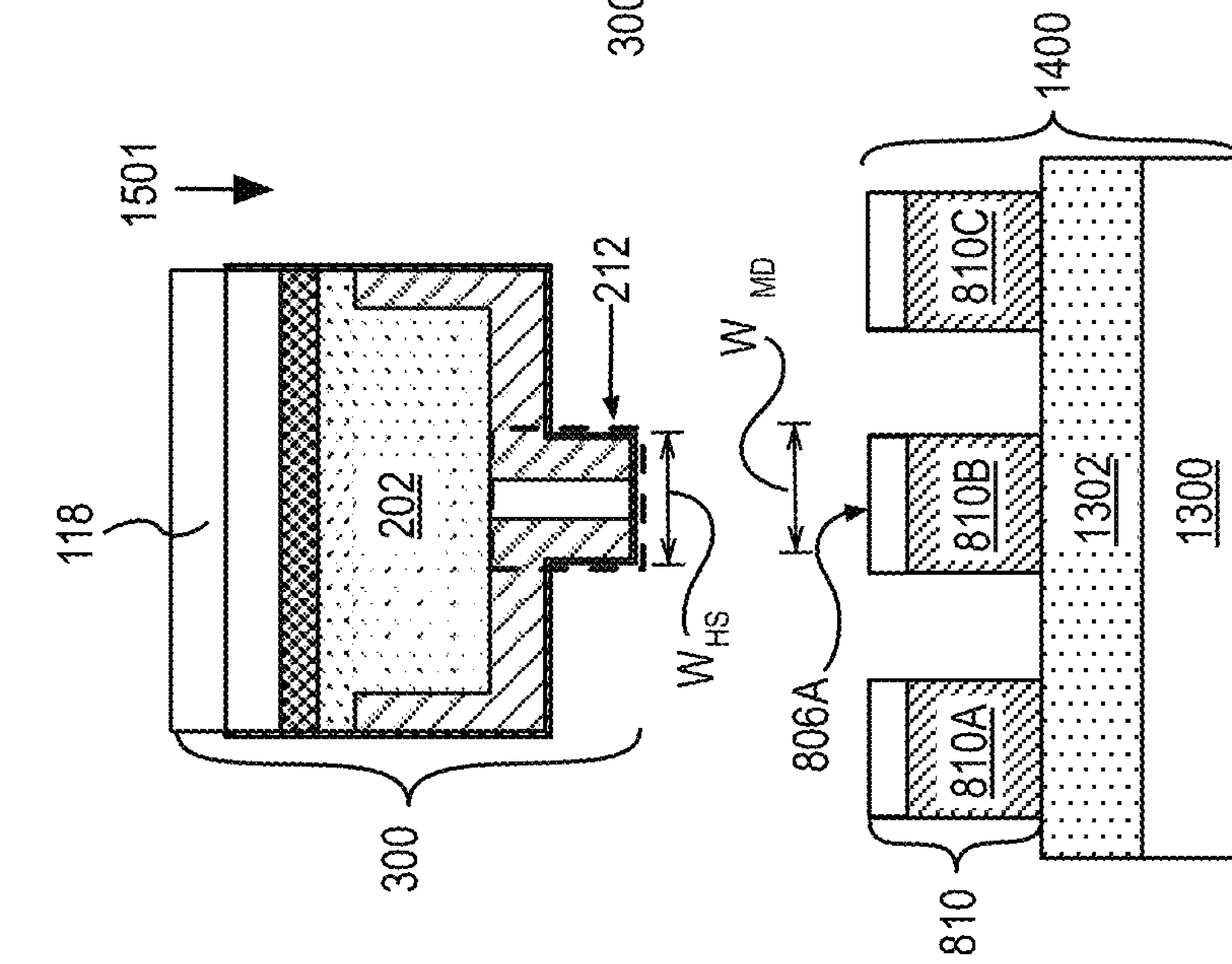


FIG. 15A

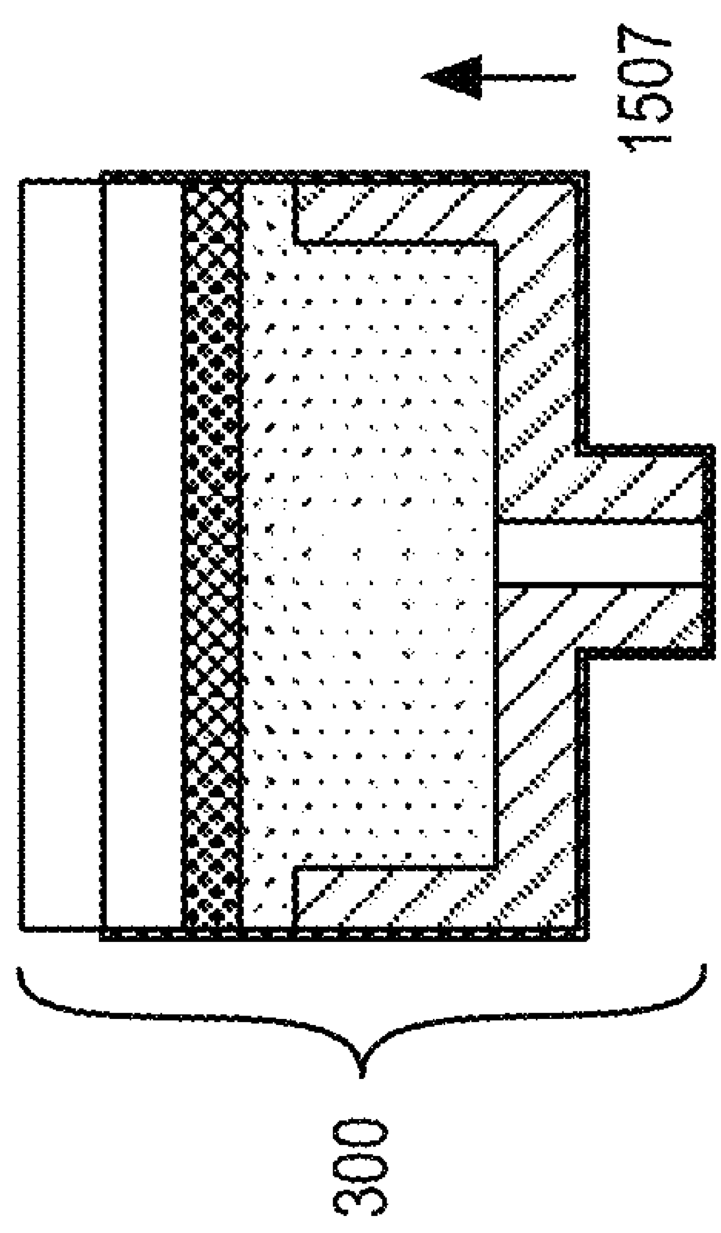


FIG. 15F

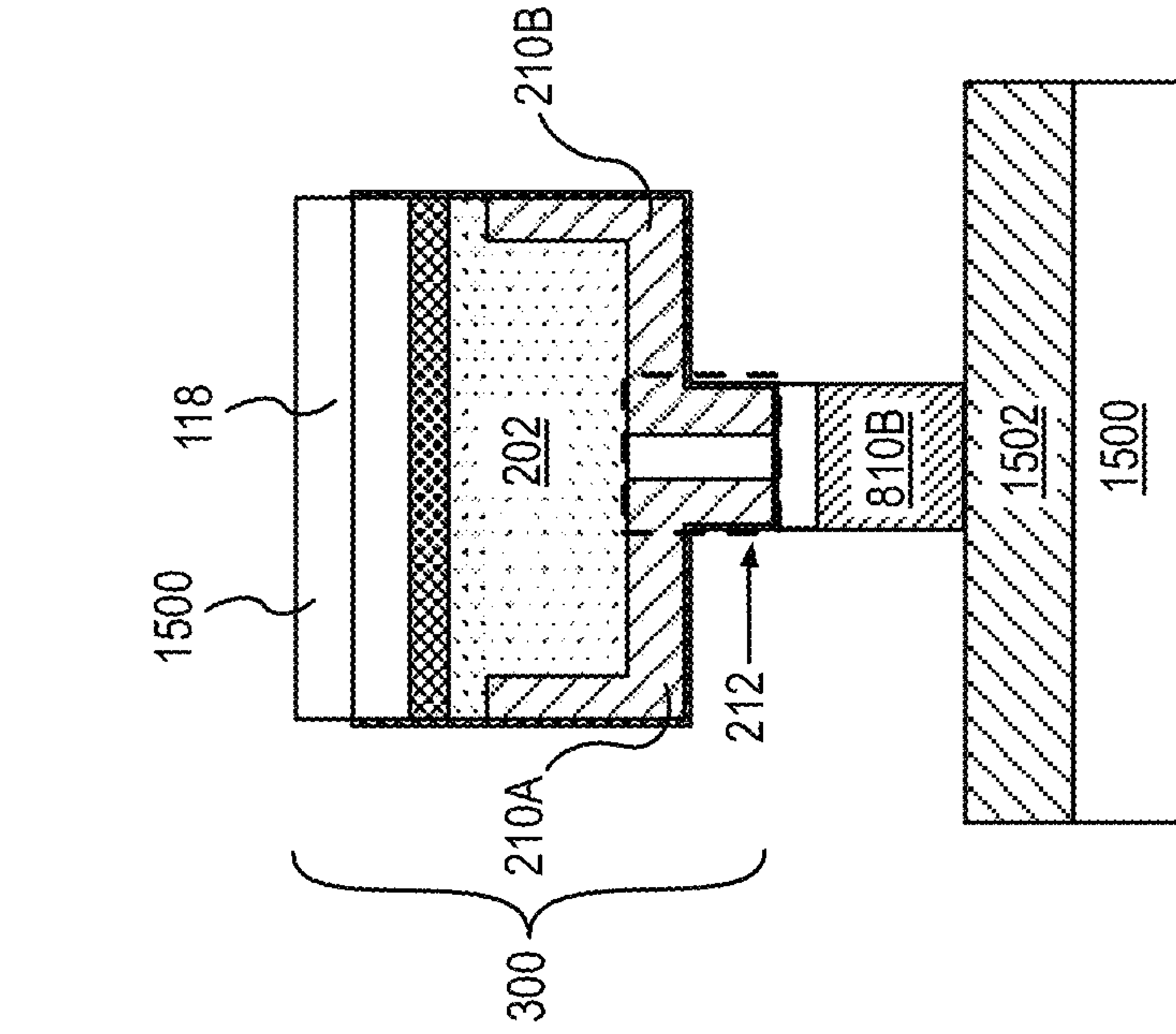


FIG. 15E

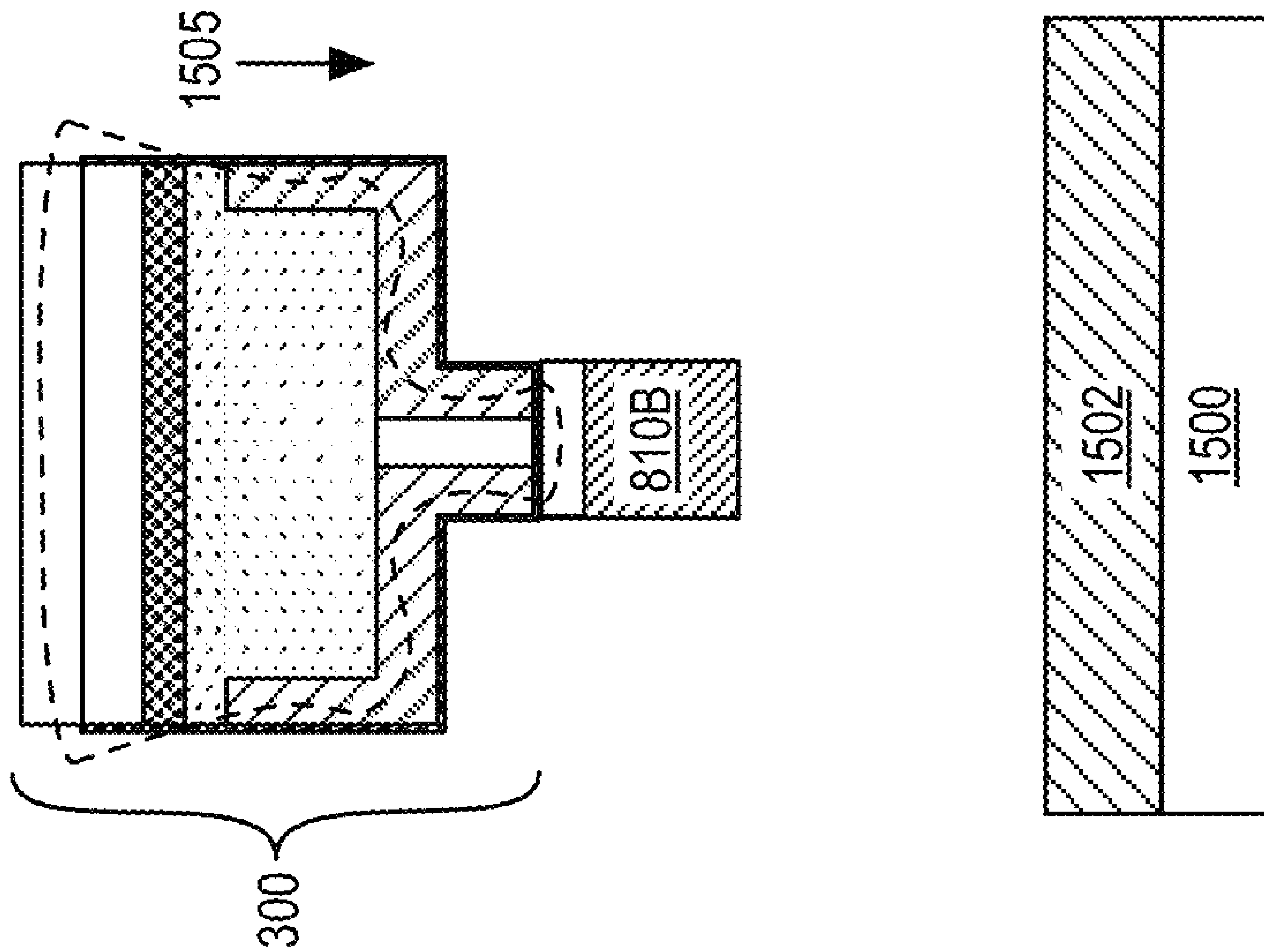


FIG. 15D

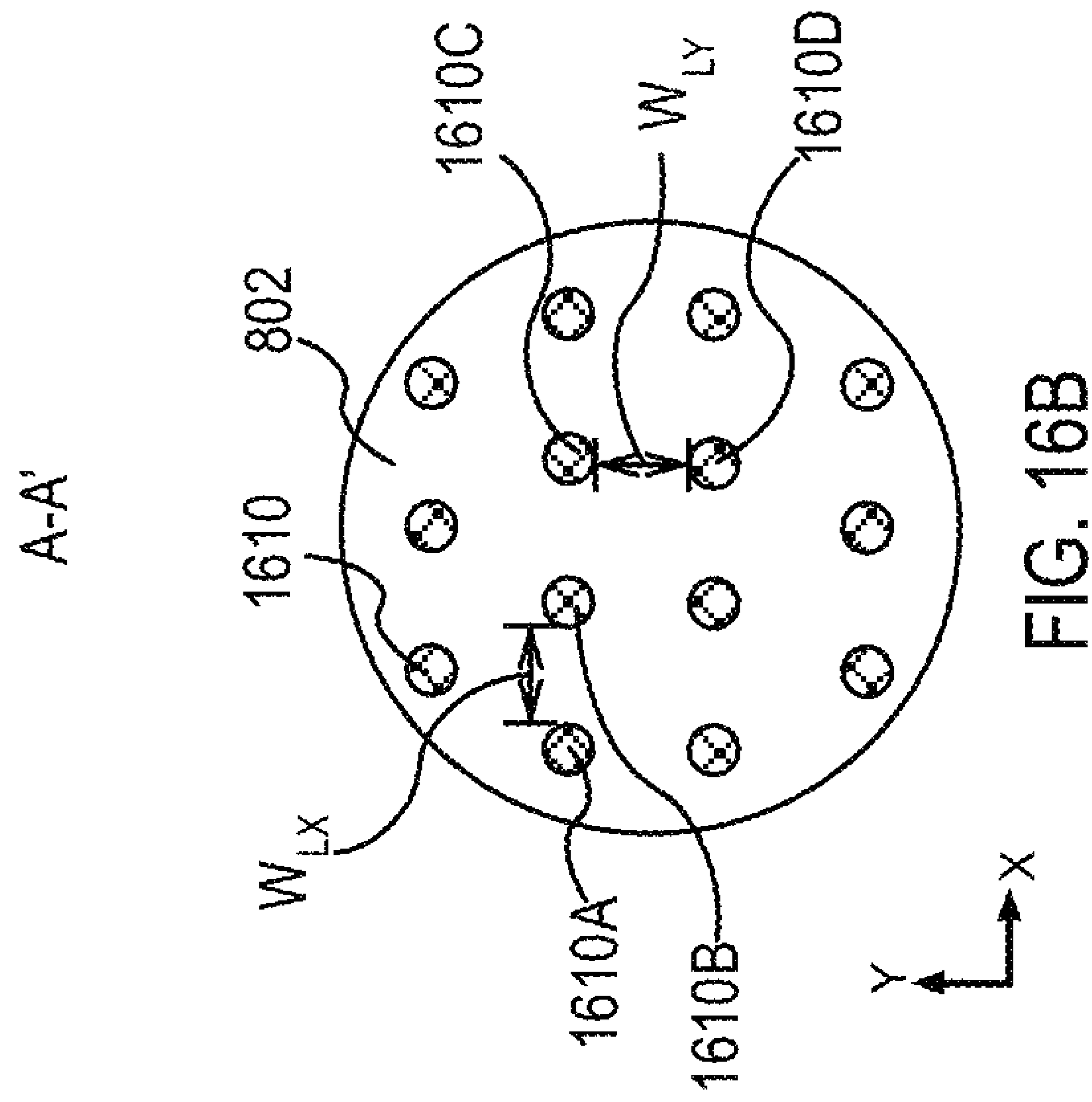


FIG. 16B

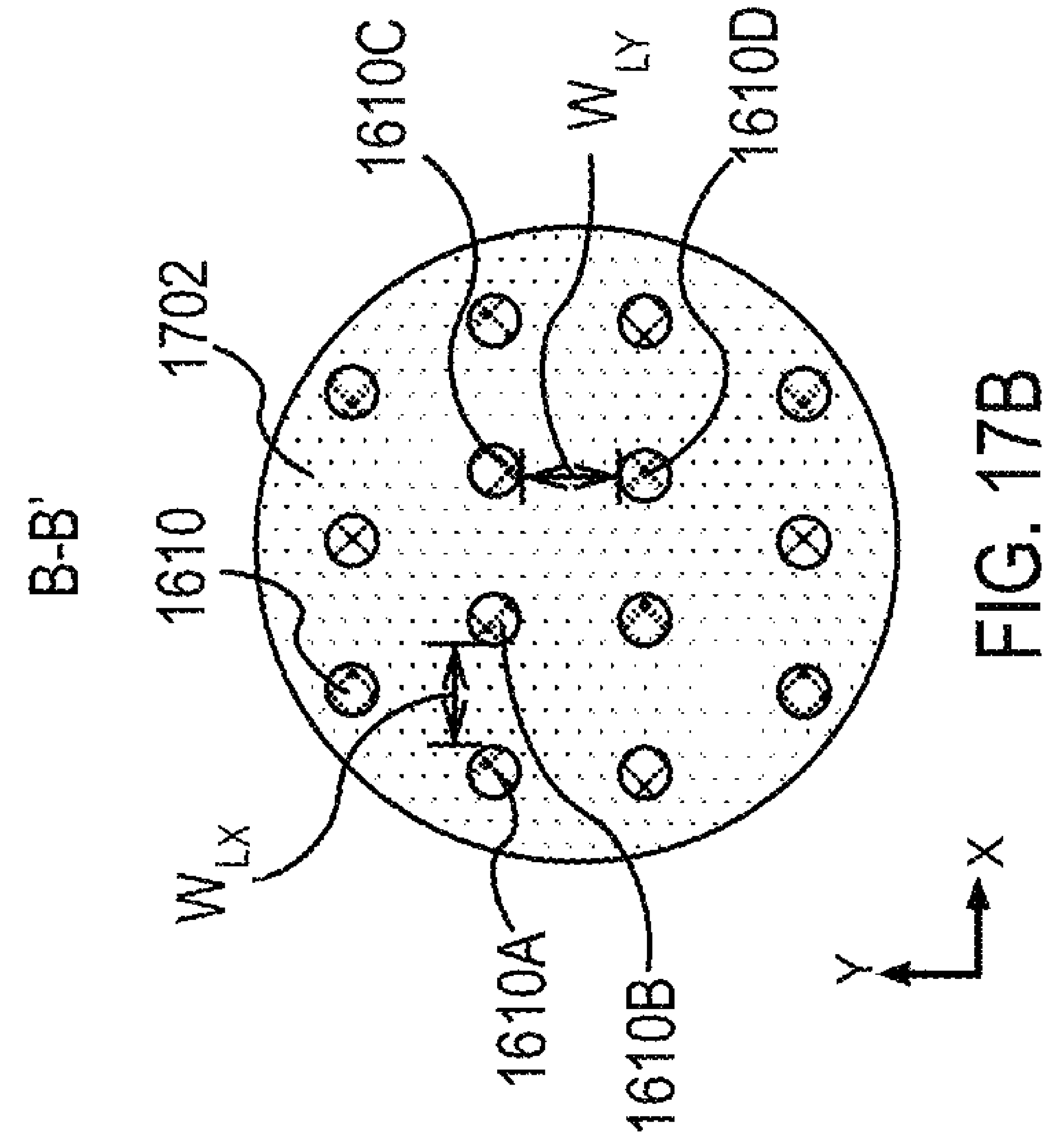
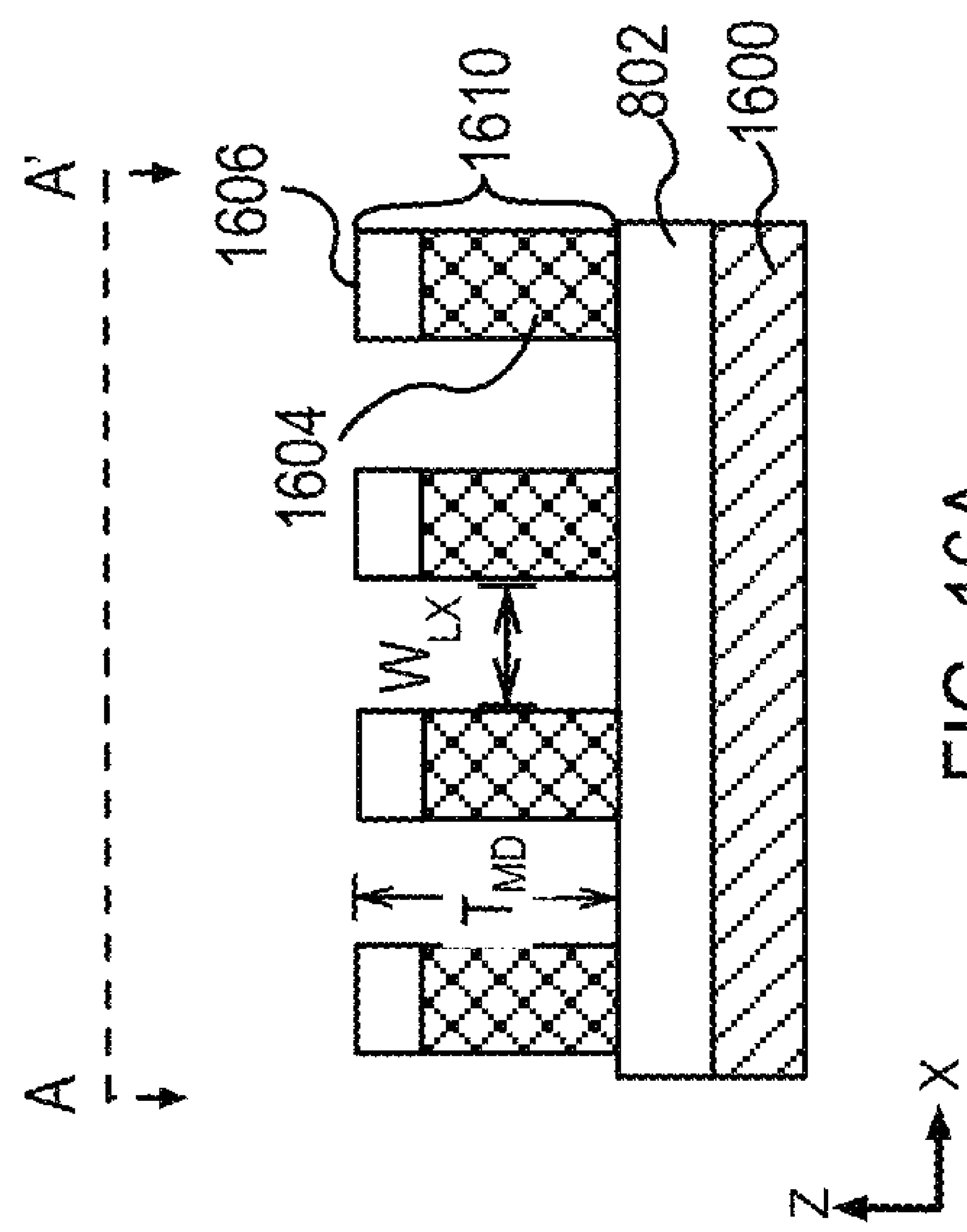


FIG. 17B



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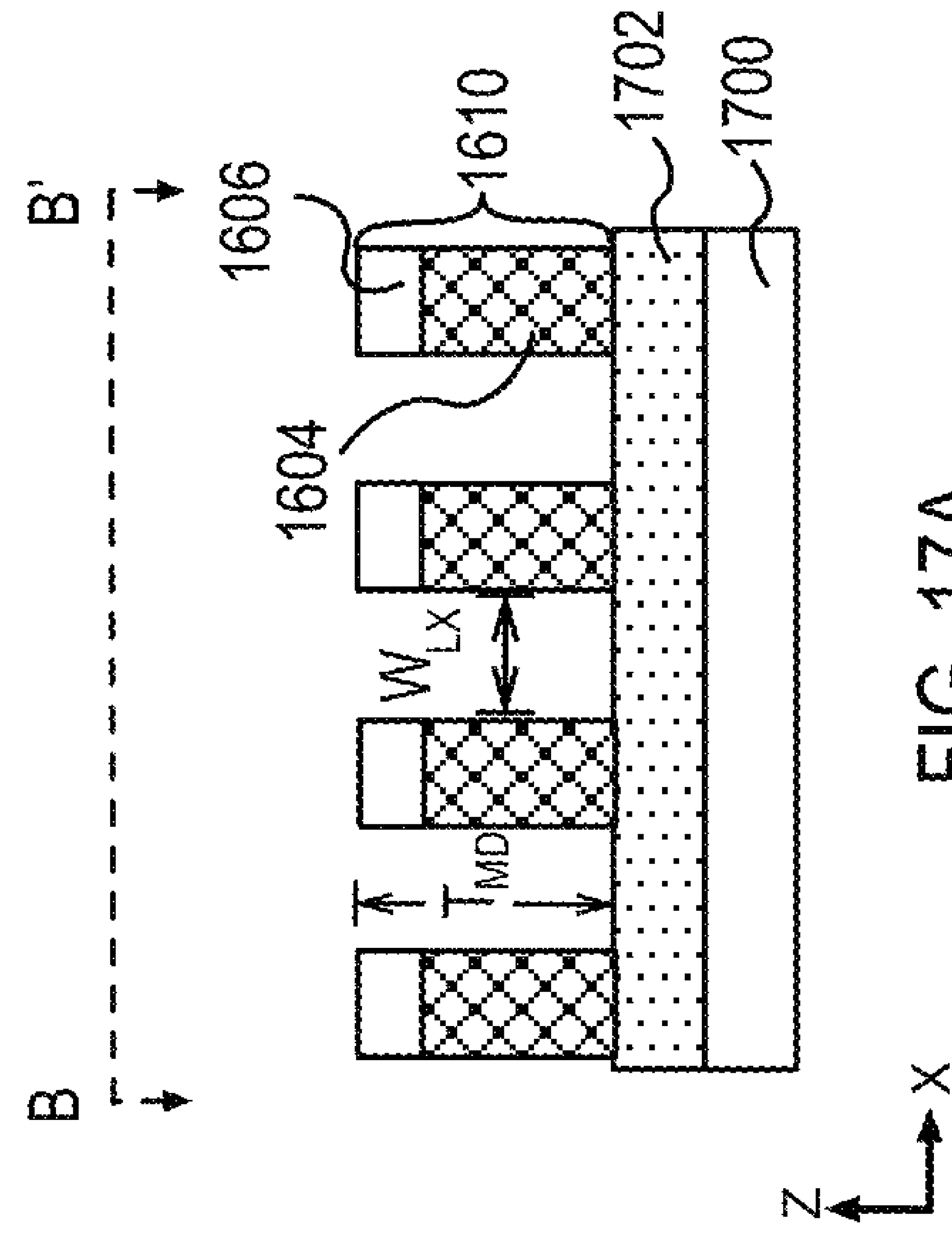


FIG. 17A

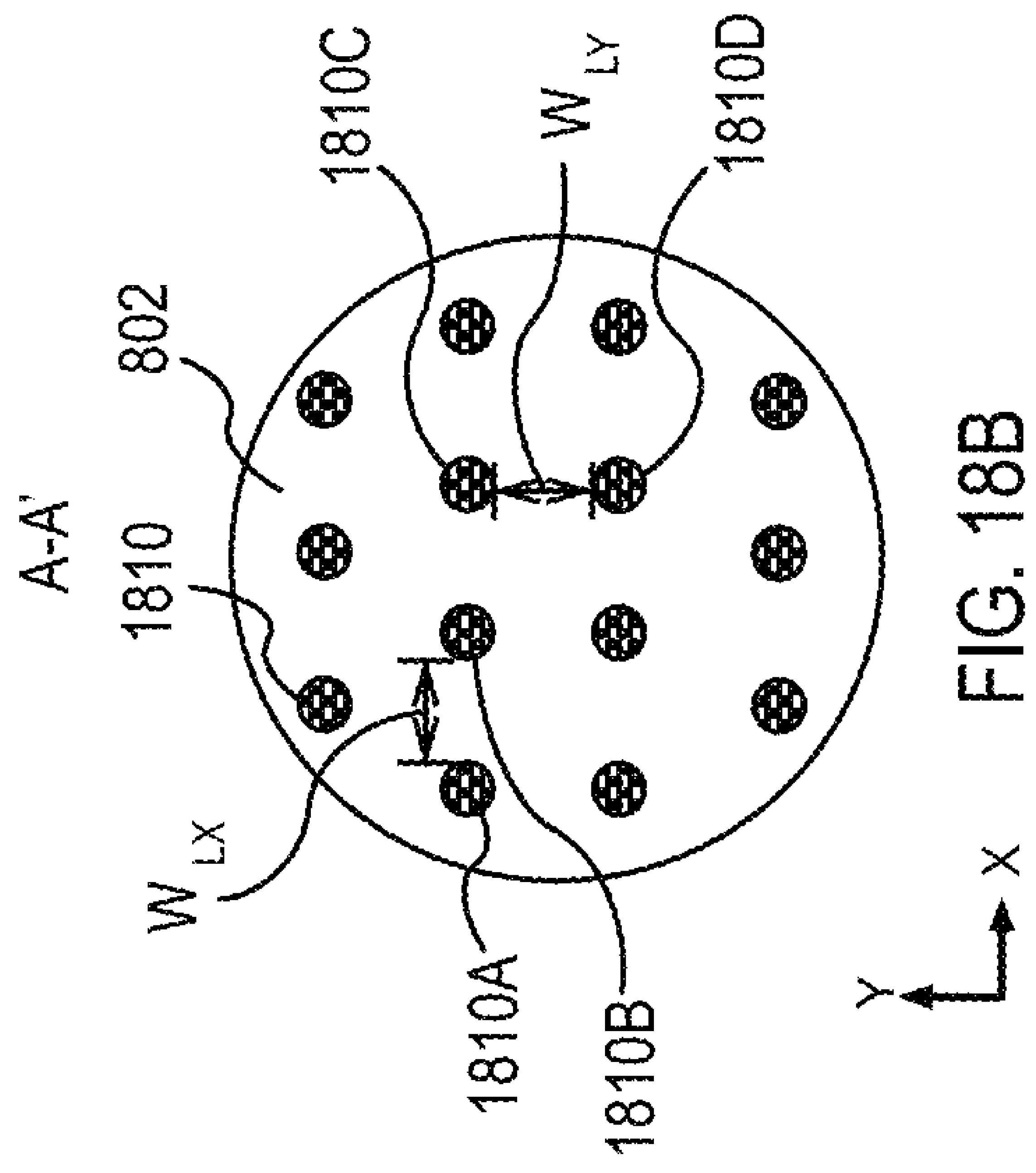
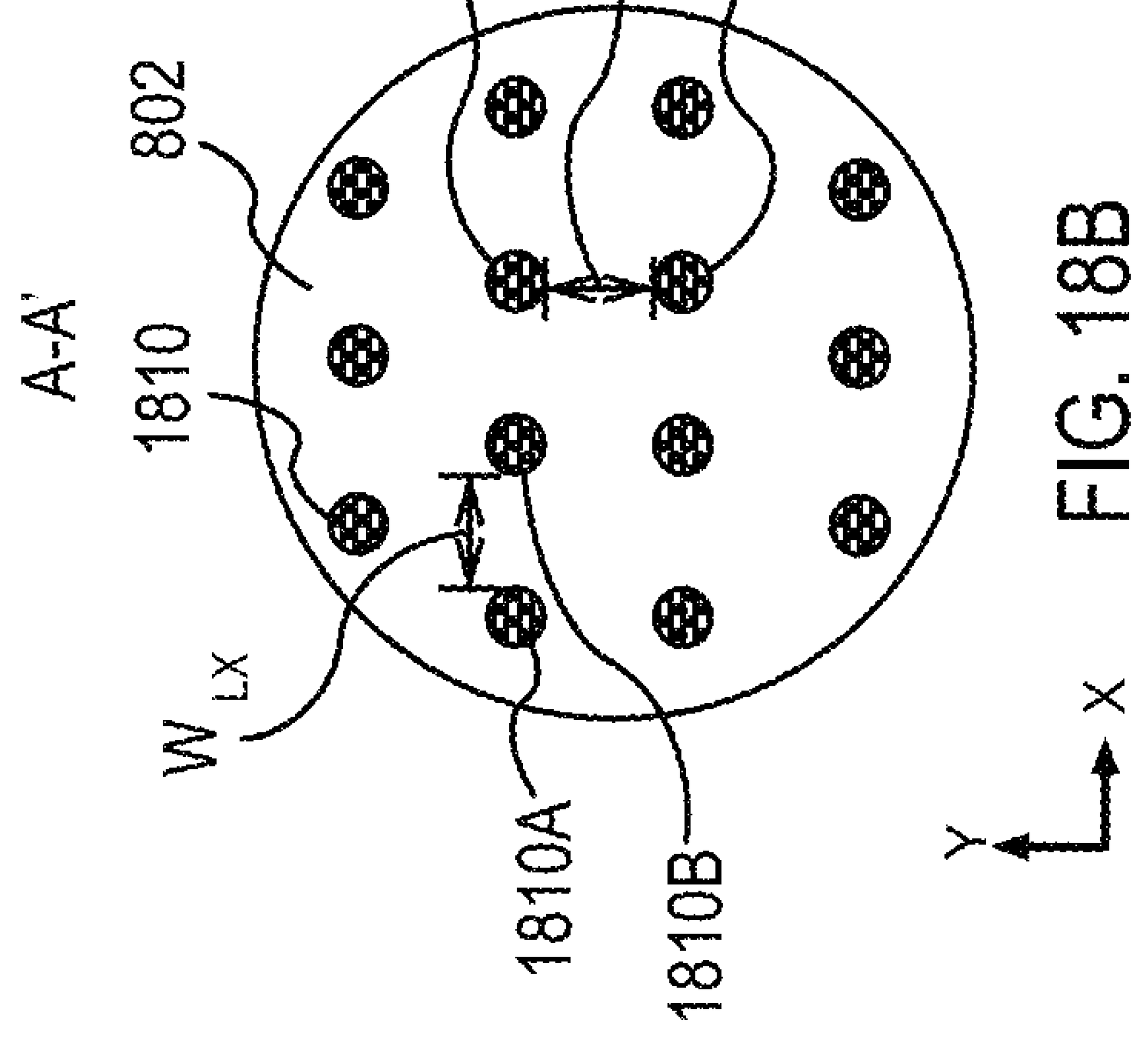



FIG. 18B

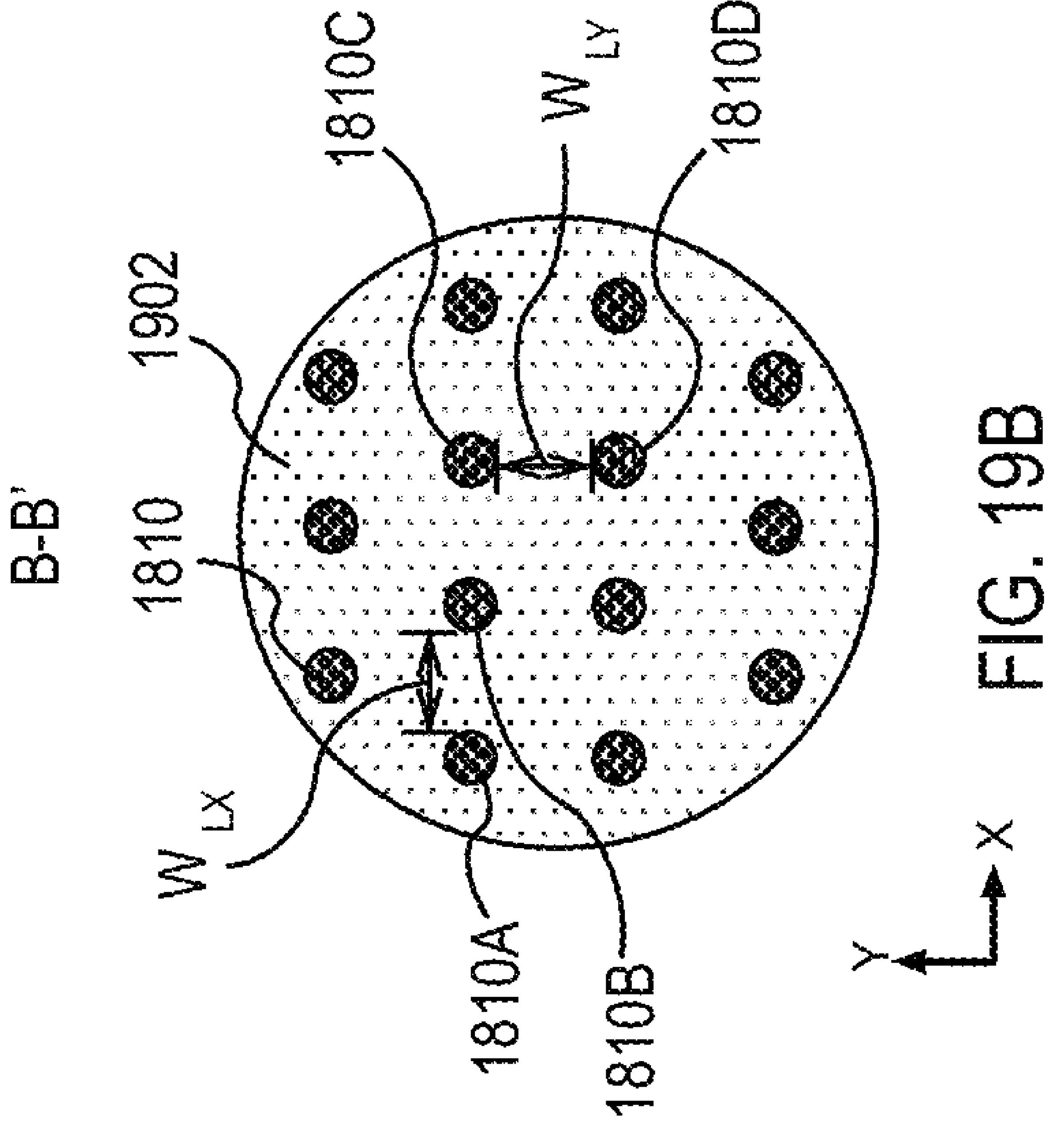
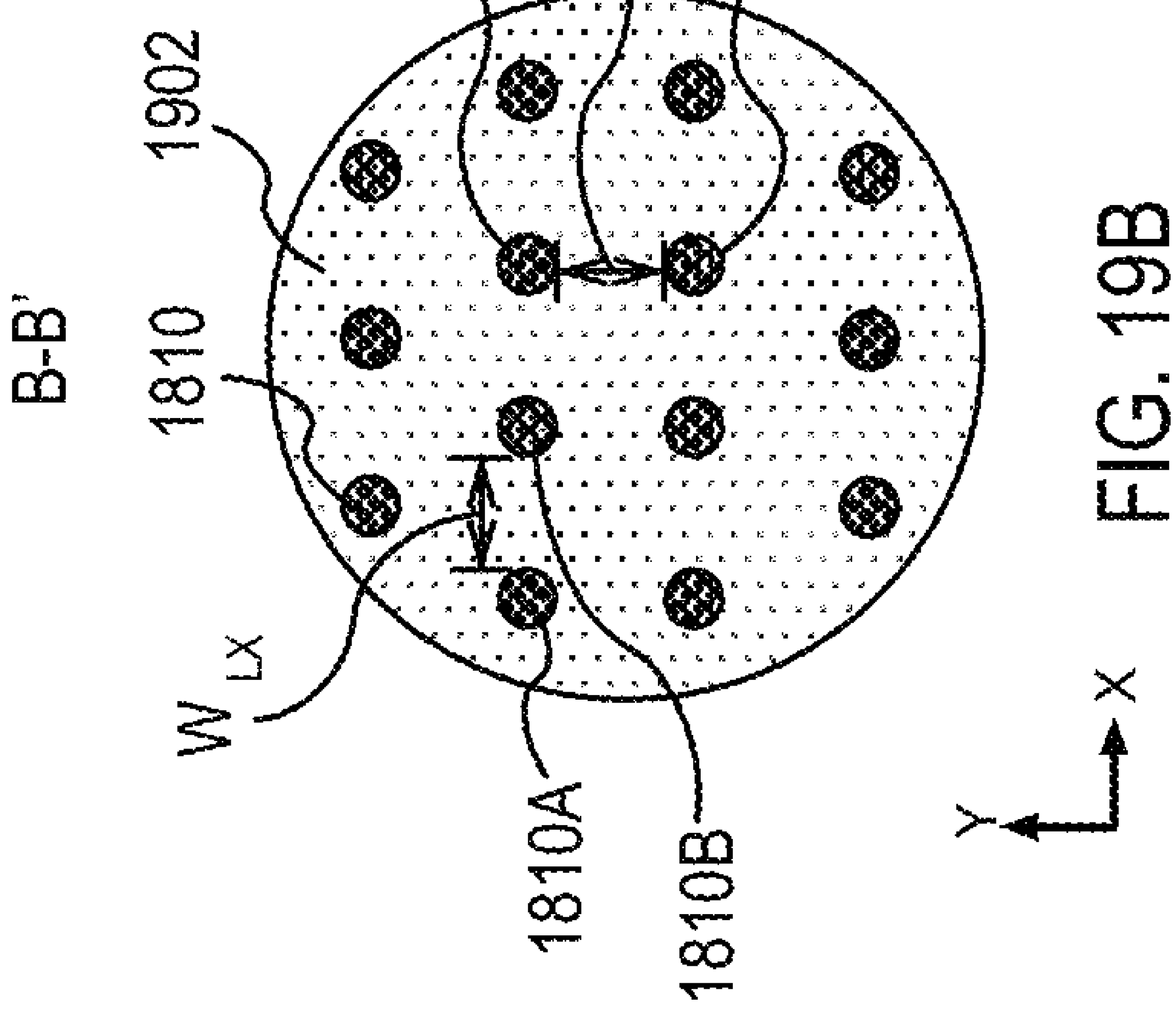



FIG. 19B

A A'
1806
1810
802
1800
1804
W_{LX}
T_{MD}
Z X

FIG. 18A

B B'
1806
1810
1902
1900
1804
W_{LX}
T_{MD}
Z X

FIG. 19A

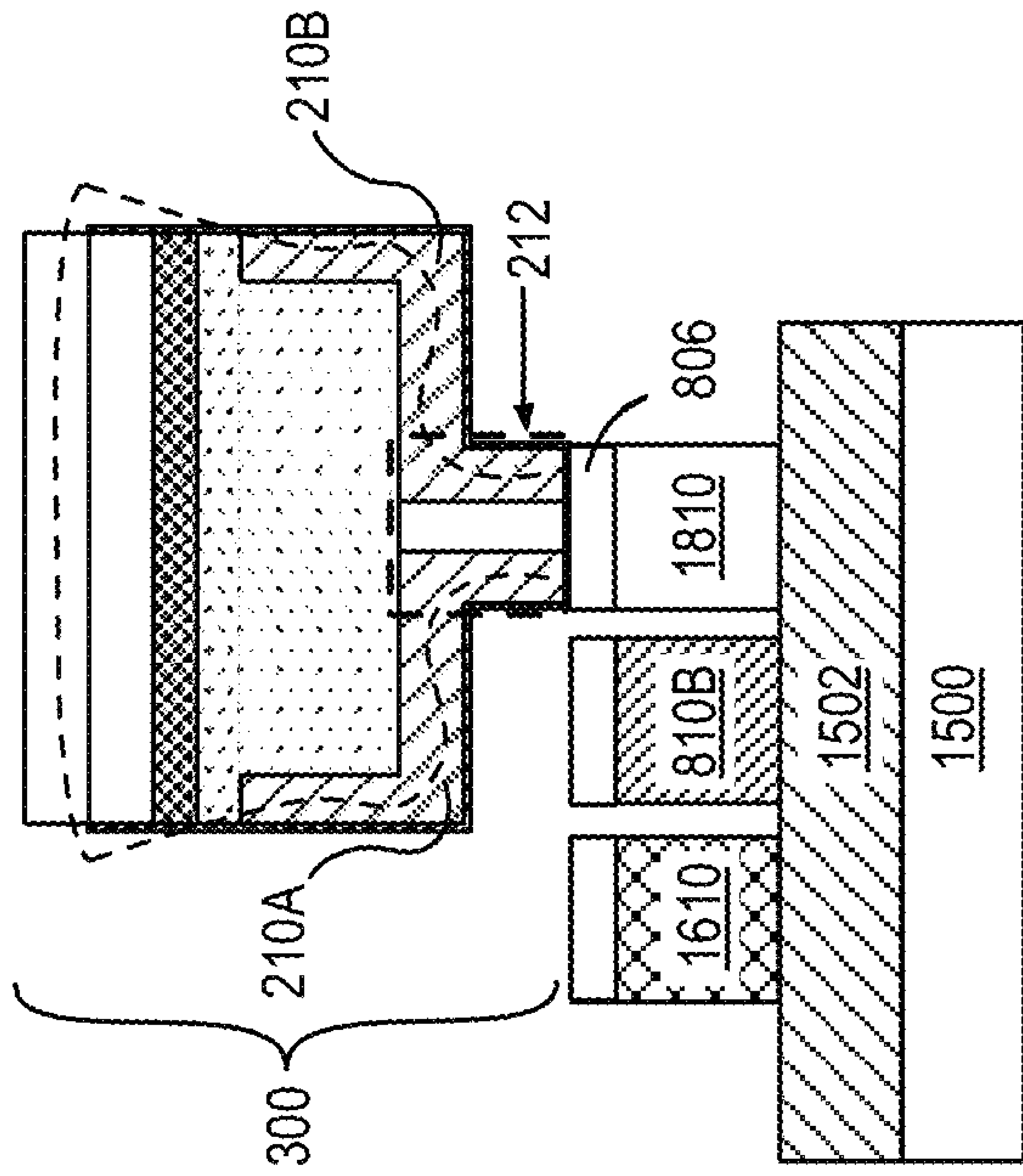


FIG. 20B

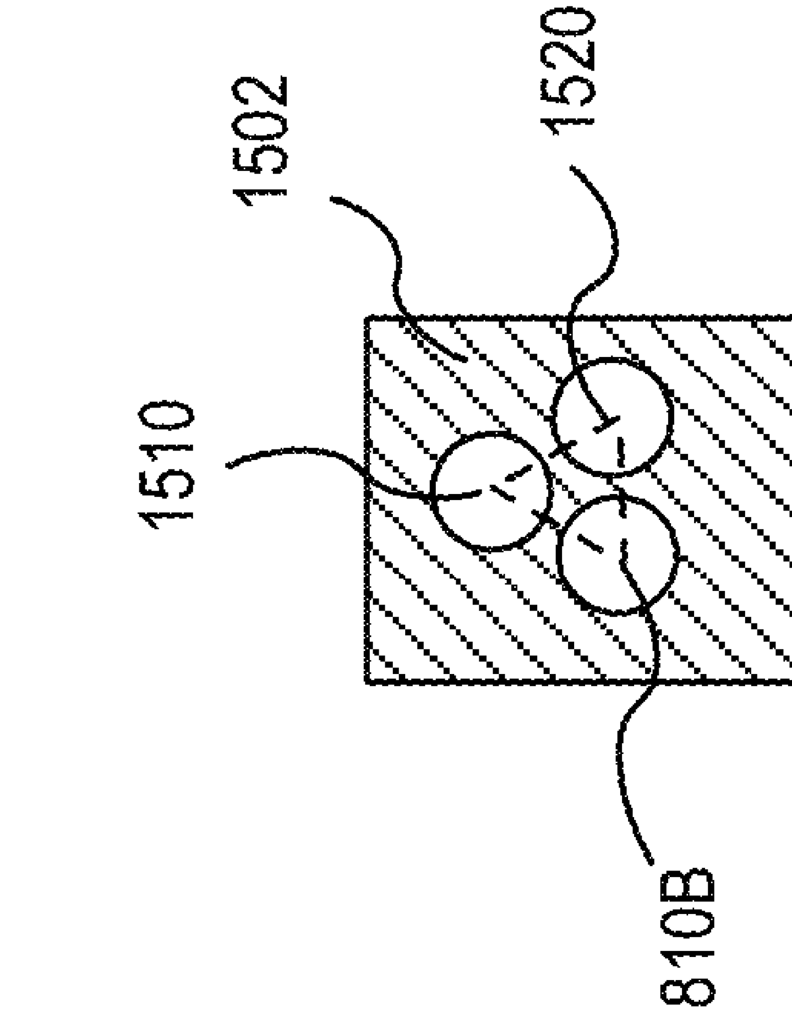
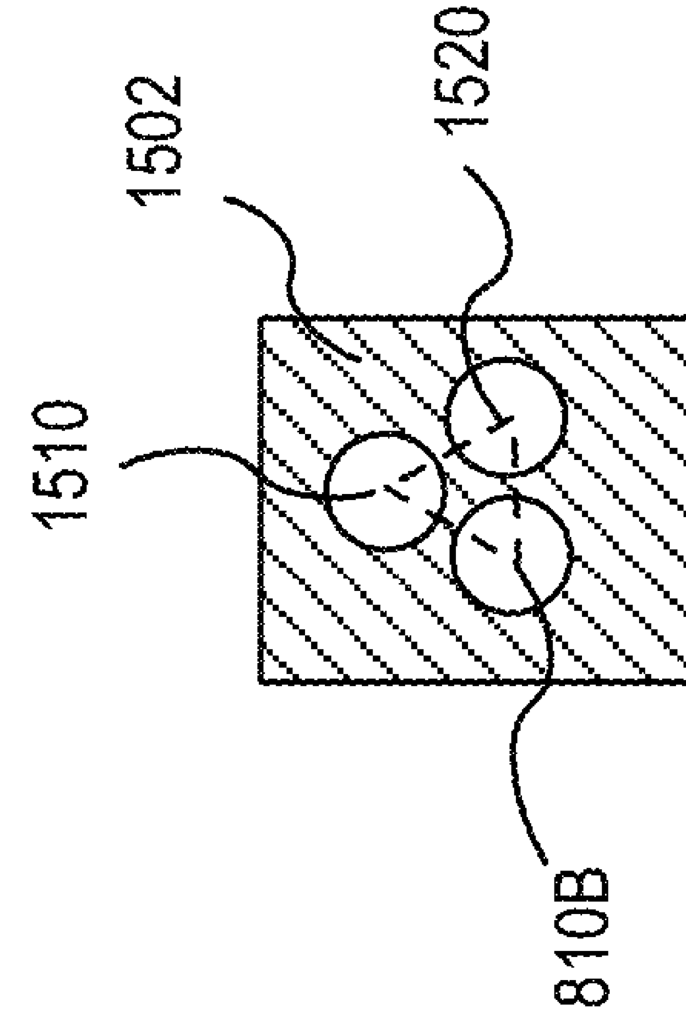



FIG. 21

FIG. 20A

300
118
1500
210B
202
210A
212
806
810B
1610
1502
1500
T_{MD}
W_{MD}

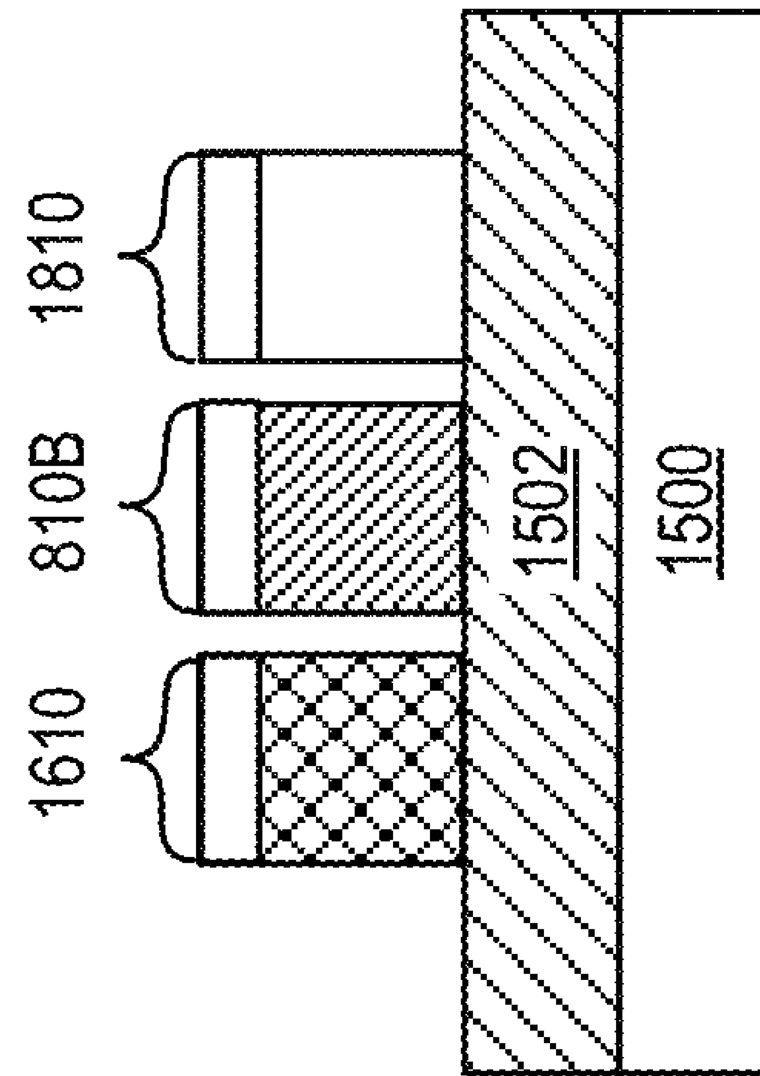
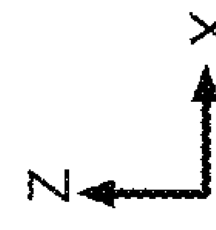


FIG. 20C



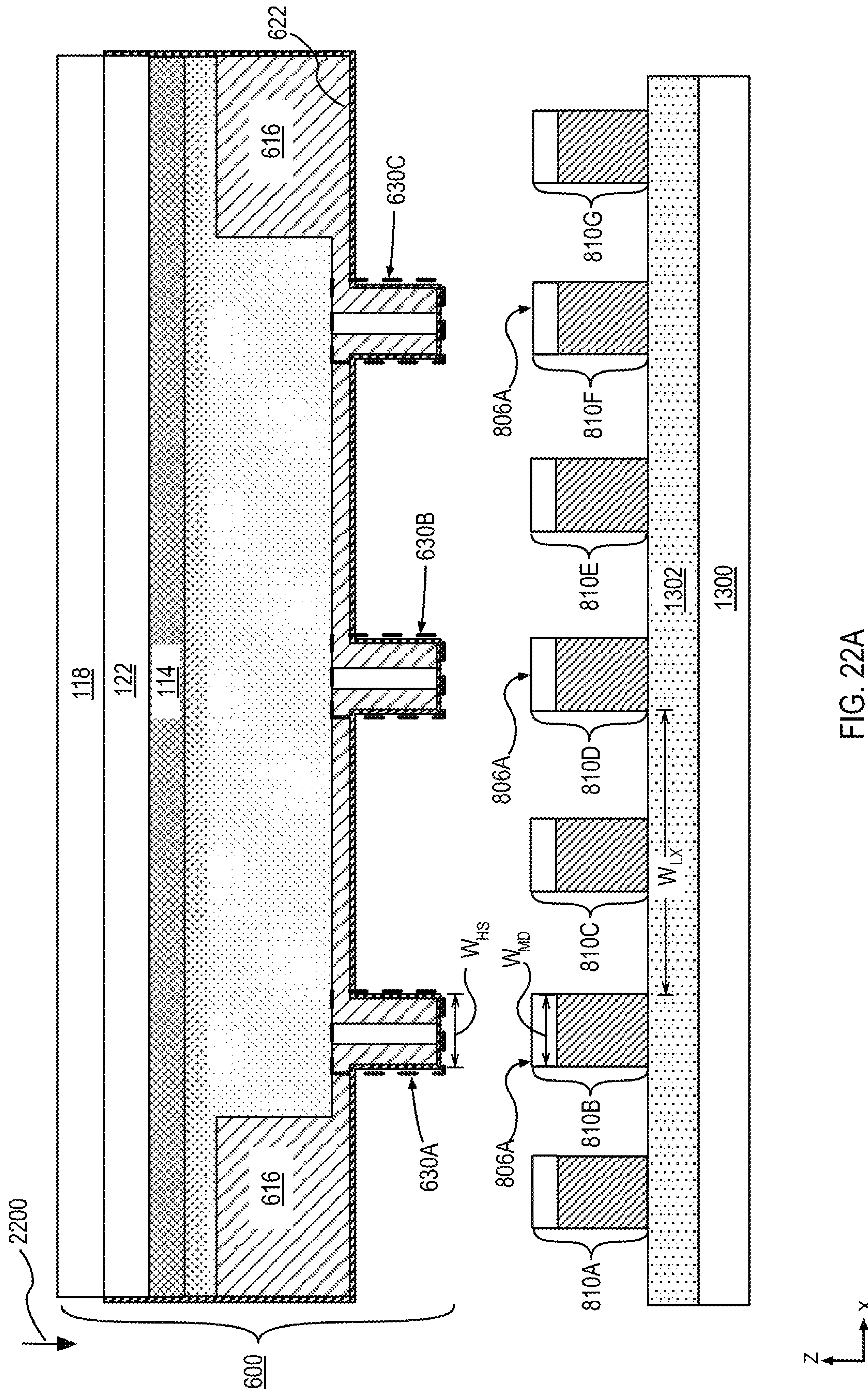


FIG. 22A

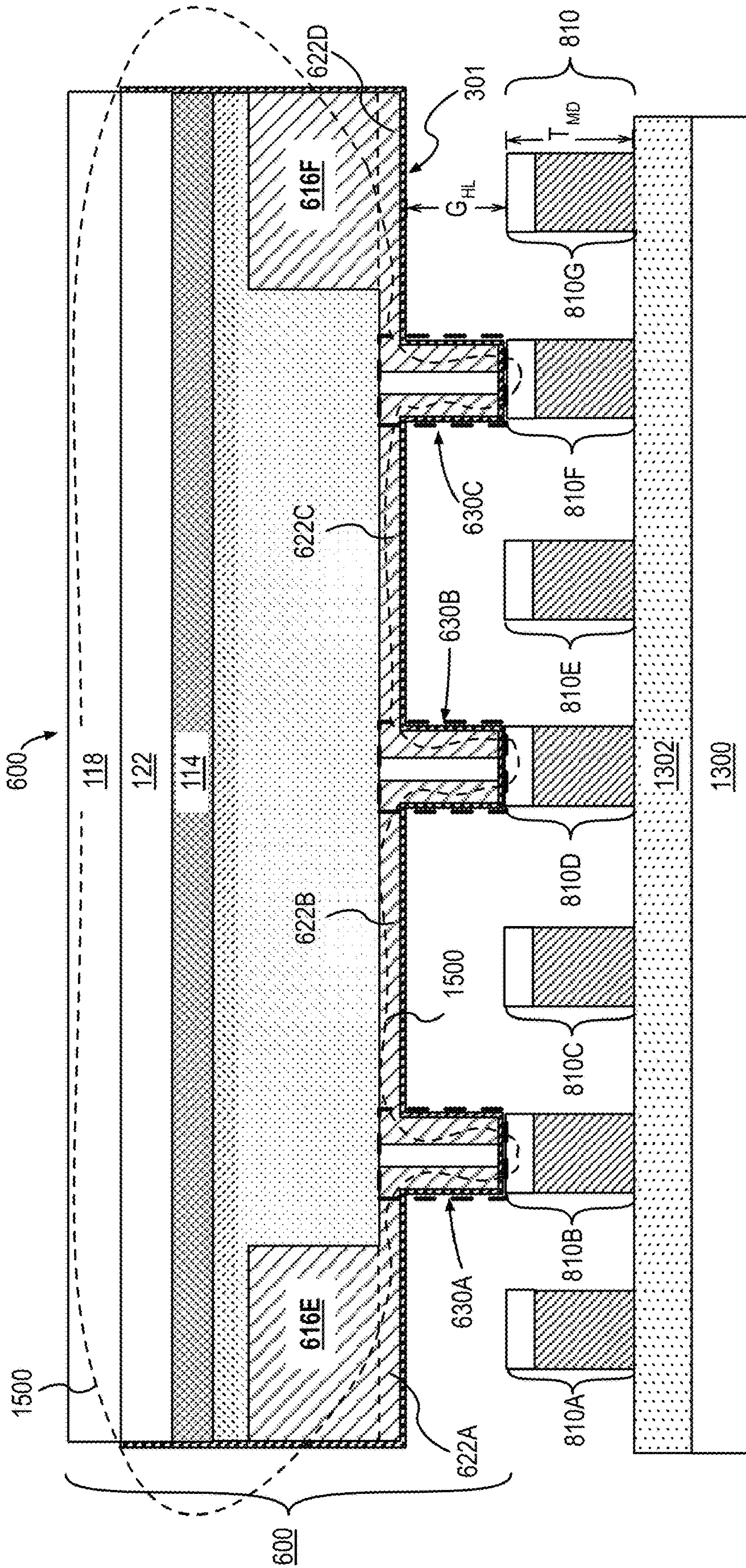


FIG. 22B

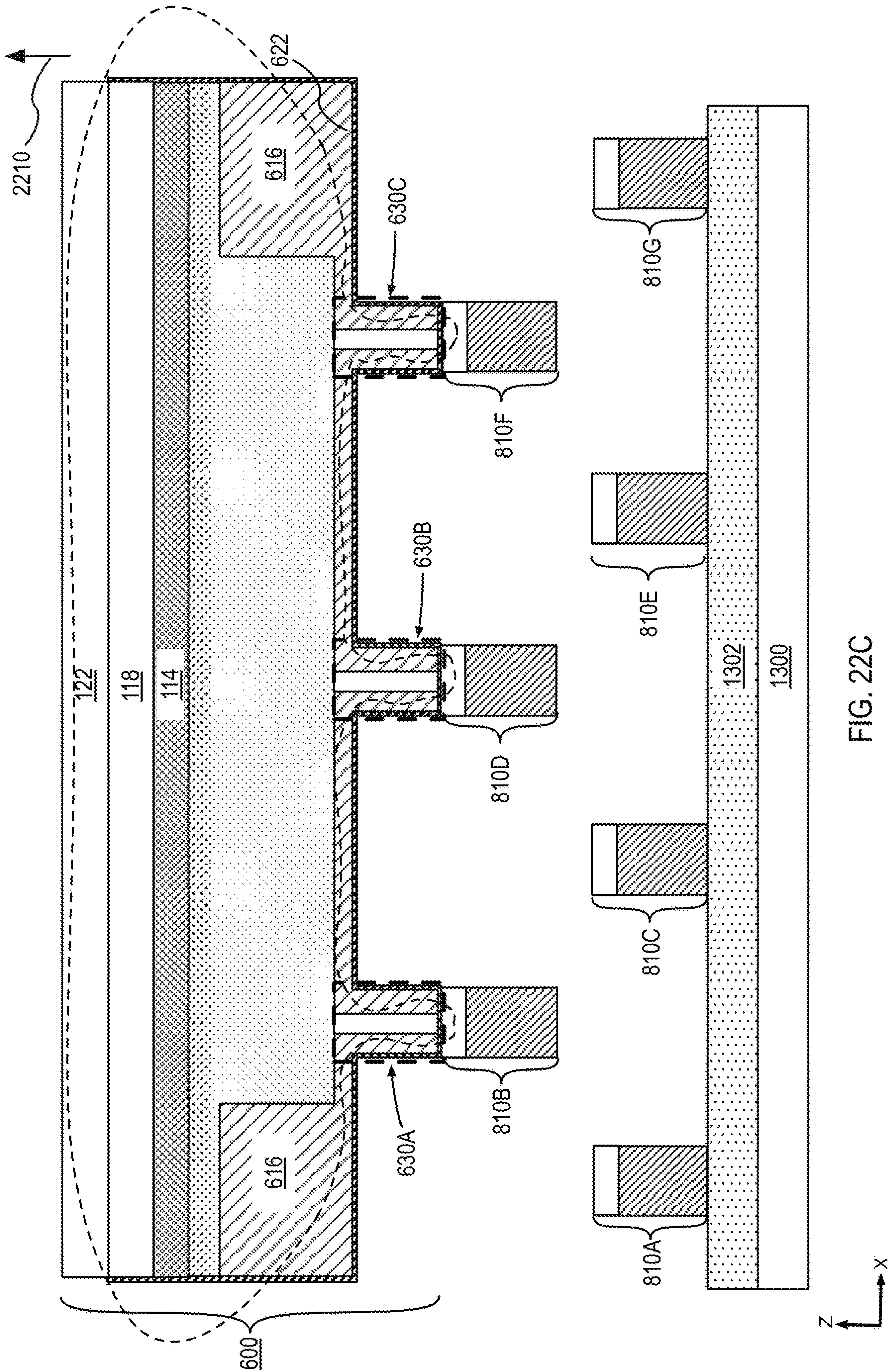


FIG. 22C

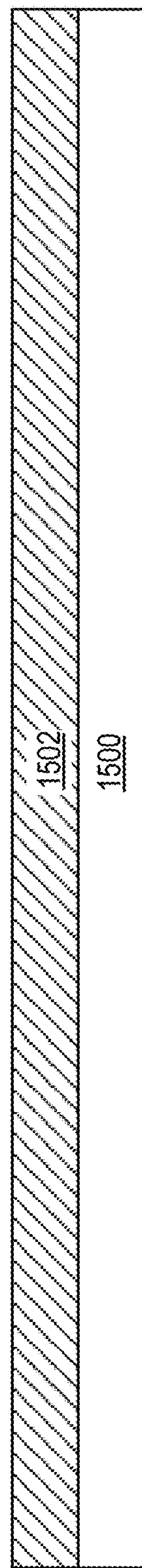


FIG. 22D

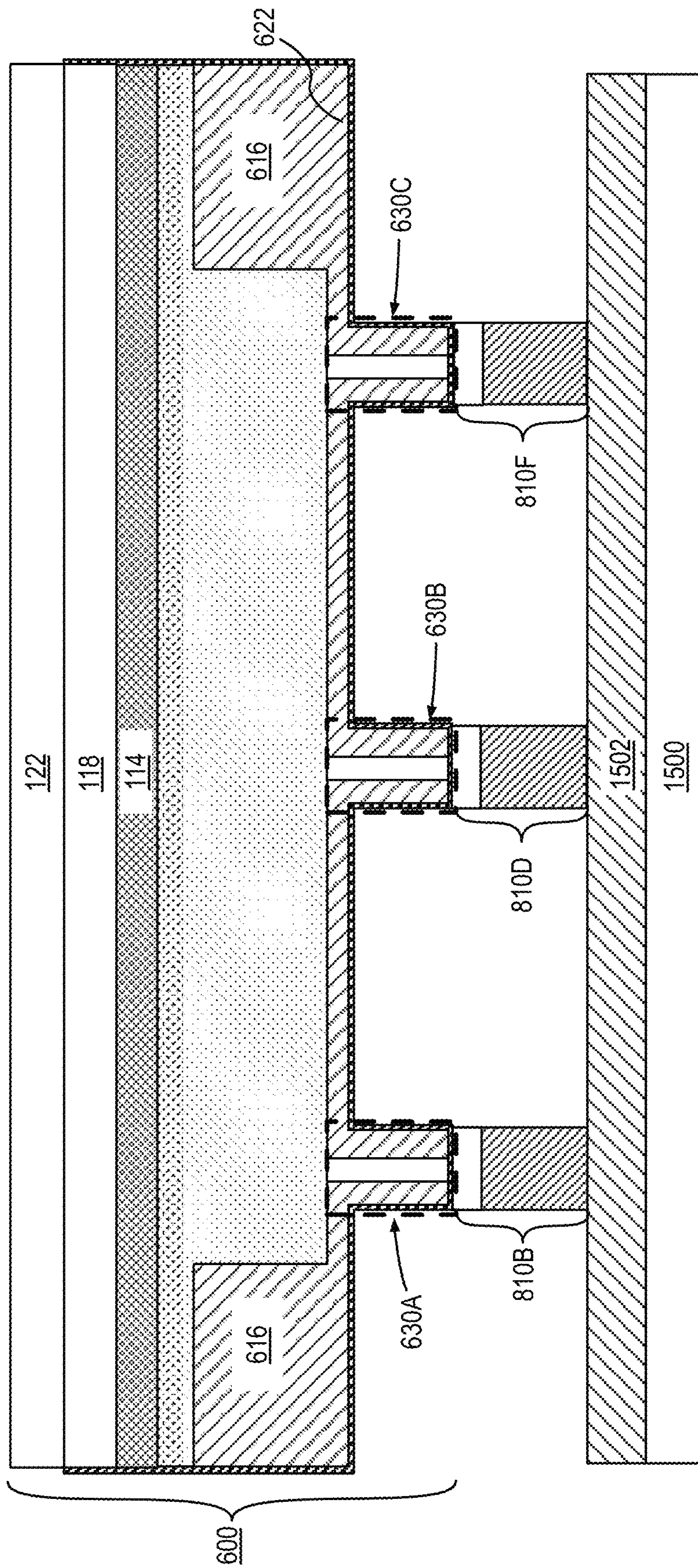


FIG. 22E

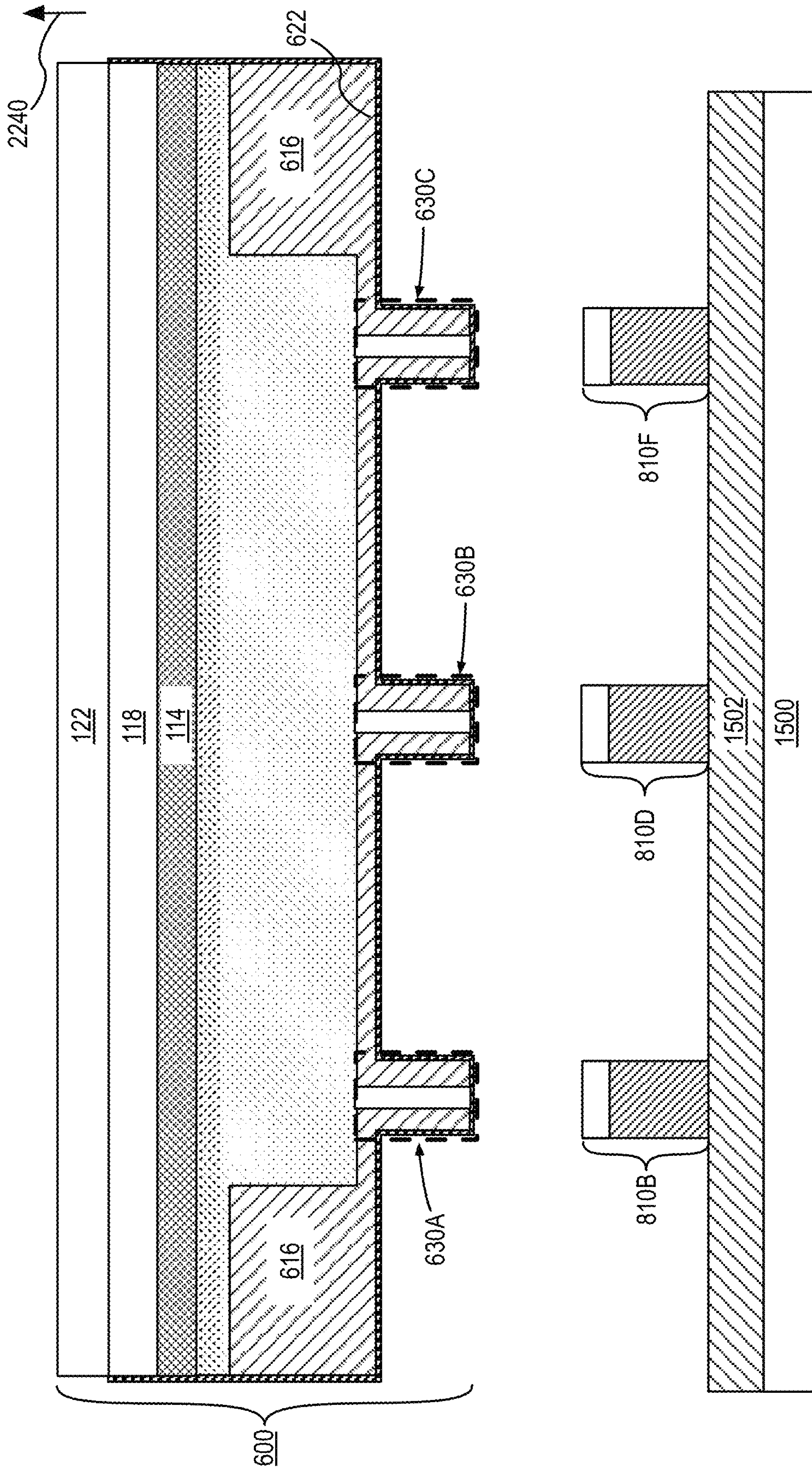


FIG. 22F

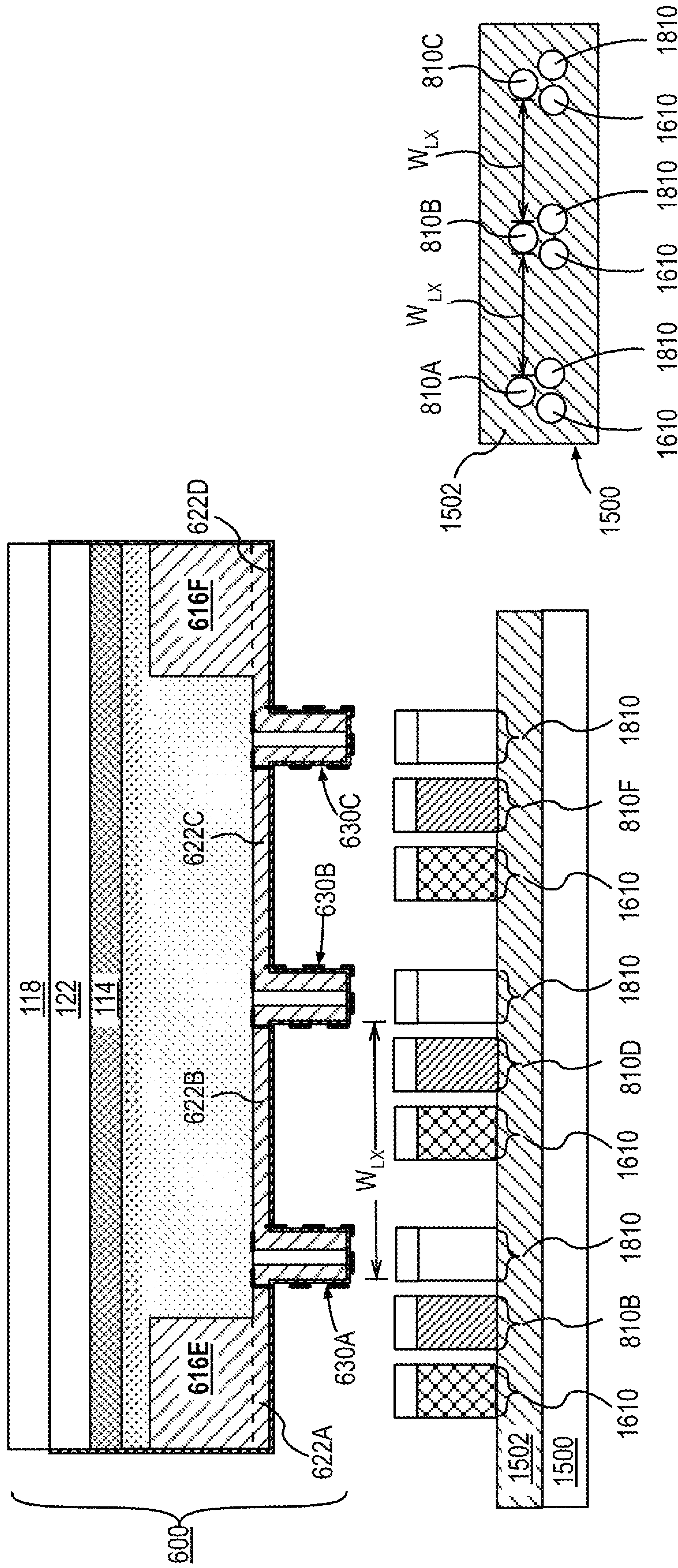


FIG. 23A

FIG. 23B

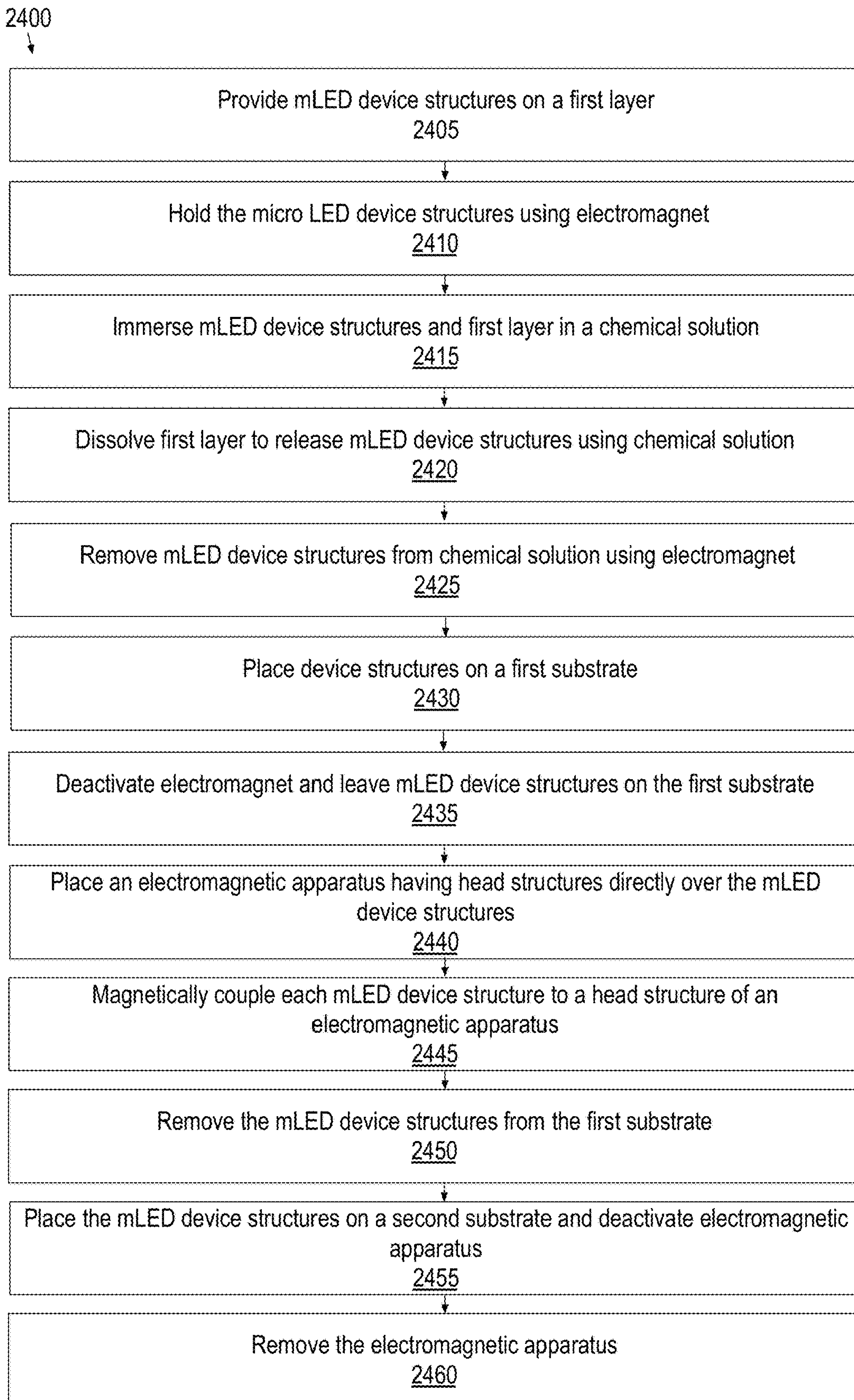


FIG. 24

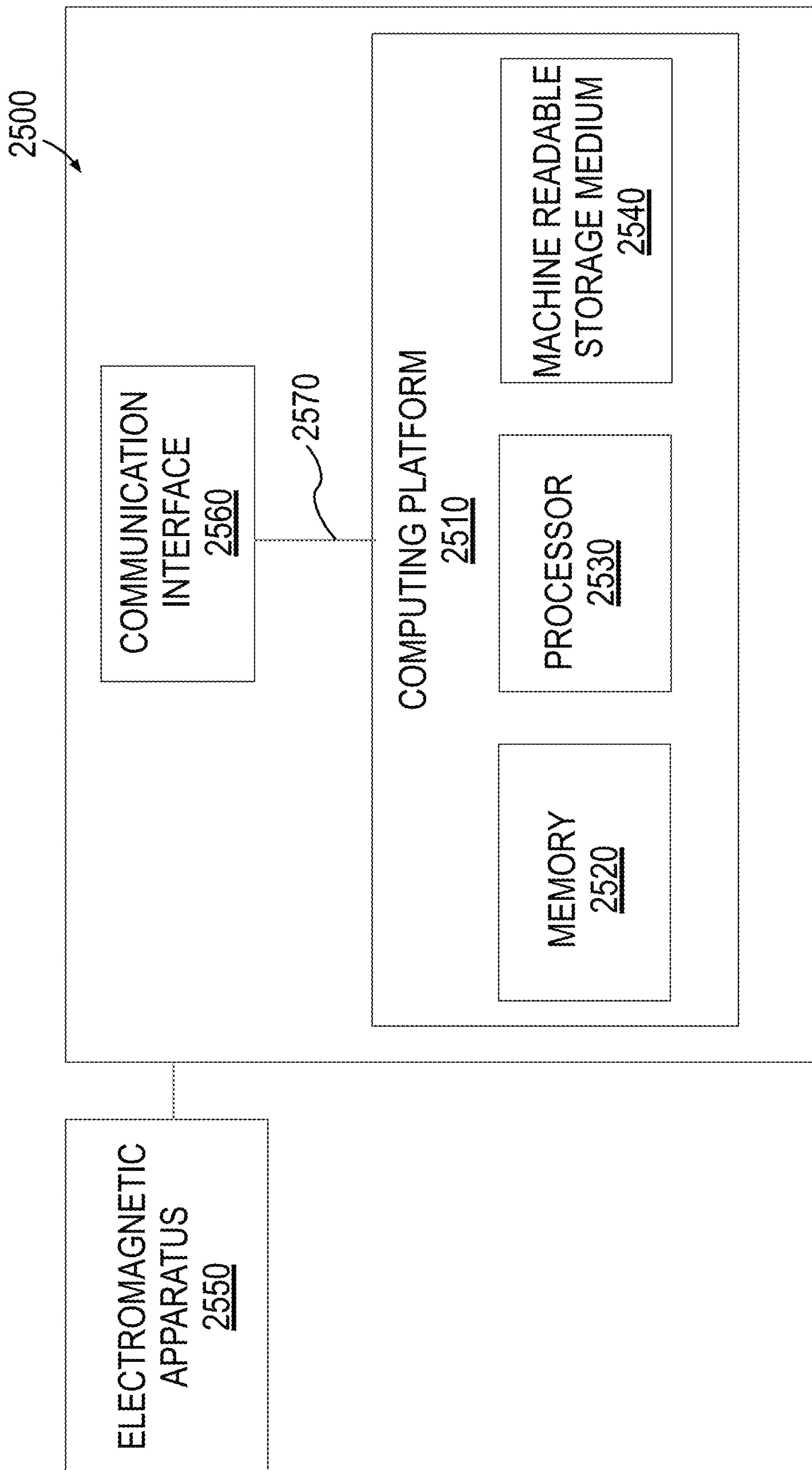


FIG. 25

ELECTROMAGNETIC TOOL FOR TRANSFERRING MICRO DEVICES AND METHODS OF FABRICATION

BACKGROUND

Recently, enabling massive parallel transfer of micro-structures has received intense focus, especially in the field of micro-LED (mLED) based display. Development of capabilities for parallel transfer of large volumes of mLED devices can enable high volume manufacturability of mLED device-based display.

However, it is a formidable technical challenge to selectively move large number of mLEDs between different substrates under typical manufacturing variabilities in mLED height and critical dimensions. It has thus become increasingly relevant to develop transfer technology that is both selective and tolerant to variation in mLED device height.

BRIEF DESCRIPTION OF THE DRAWINGS

The material described herein is illustrated by way of example, and not by way of limitation in the accompanying figures. For simplicity and clarity of illustration, elements illustrated in the figures are not necessarily drawn to scale. For example, the dimensions of some elements may be exaggerated relative to other elements for clarity. Also, various physical features may be represented in their simplified "ideal" forms and geometries for clarity of discussion. Thus, it is to be understood that practical implementations may only approximate the illustrated ideals. For example, smooth surfaces and square intersections may be drawn in disregard of finite roughness, corner-rounding, and imperfect angular intersections, characteristic of structures formed by nanofabrication techniques. Further, where considered appropriate, reference labels have been repeated among the figures to indicate corresponding or analogous elements.

FIG. **1**A illustrates a cross-sectional view of an electromagnetic apparatus, in accordance with an embodiment of the present disclosure.

FIG. **1**B illustrates an isometric view of the electromagnetic apparatus depicted in FIG. **1**A, in accordance with an embodiment of the present disclosure.

FIG. **1**C illustrates a cross section of an electromagnetic apparatus, where sidewalls of the isolation structure are tapered, in accordance with an embodiment of the present disclosure.

FIG. **2**A illustrates a cross-sectional view of an electromagnetic apparatus, in accordance with an embodiment of the present disclosure.

FIG. **2**B illustrates an isometric view of the electromagnetic apparatus depicted in FIG. **2**A, in accordance with an embodiment of the present disclosure.

FIG. **3**A illustrates a cross-sectional view of an electromagnetic apparatus coated with a hermetic seal, in accordance with an embodiment of the present disclosure.

FIG. **3**B illustrates an isometric view of the electromagnetic apparatus coated with the hermetic seal depicted in FIG. **3**A, in accordance with an embodiment of the present disclosure.

FIG. **4**A illustrates a cross-sectional view of an electromagnetic apparatus including an array of pick up heads, in accordance with an embodiment of the present disclosure.

FIG. **4**B illustrates an isometric view of an electromagnetic apparatus including a plurality of arrays of pick up heads, in accordance with an embodiment of the present disclosure.

FIG. **4**C illustrates an isometric view of an electromagnetic apparatus including a plurality of independent arrays of pick up heads, in accordance with an embodiment of the present disclosure.

FIG. **5** illustrates a flow diagram depicting the method to make an electromagnetic apparatus, in accordance with an embodiment of the present disclosure.

FIG. **6**A illustrates a first layer of non-magnetic material formed above a substrate.

FIG. **6**B illustrates a cross-sectional view of the structure in FIG. **6**A following the formation of a first mask on the first layer of non-magnetic material.

FIG. **6**C illustrates a cross-sectional view of the structure in FIG. **6**B following the formation of a second layer of non-magnetic material on a portion of the first layer of non-magnetic material.

FIG. **6**D illustrates the structure of FIG. **6**C following the removal of the first mask followed by a formation of a second mask on the second layer of non-magnetic material.

FIG. **6**E illustrates the structure of FIG. **6**D following the formation of a first layer of magnetic material on portions of the first layer of non-magnetic material.

FIG. **6**F illustrates the structure of FIG. **6**E following removal of the second mask and planarization of the second layer of non-magnetic material and the first layer of magnetic material.

FIG. **6**G illustrates the structure of FIG. **6**H following the formation of a plurality of structures including a dielectric material on portions of the second layer of non-magnetic material.

FIG. **6**H illustrates the structure of FIG. **6**G following the formation of a second layer of magnetic material preferentially on the first layer of magnetic material and on the second layer of non-magnetic material.

FIG. **6**I illustrates the structure of FIG. **6**H following the formation of a third mask defining openings adjacent to each of the plurality of structures, exposing portions of the second layer of magnetic material.

FIG. **6**J illustrates the structure of FIG. **6**I following the formation of a third layer of magnetic material selectively on the second layer of magnetic material.

FIG. **6**K illustrates the structure of FIG. **6**J following the removal of the third mask.

FIG. **6**L illustrates the structure of FIG. **6**K following the formation of an encapsulation layer.

FIG. **7** illustrates an electromagnetic array apparatus above a plurality of micro devices above a substrate.

FIG. **8** is a cross-sectional illustration of a plurality of mLED devices on a sacrificial layer formed above a substrate.

FIG. **9**A is a cross-sectional illustration of the structure of FIG. **8** following the formation of a cap including a ferromagnetic material on each mLED device to form mLED device structures.

FIG. **9**B is a plan-view illustration of the structure of FIG. **9**A.

FIG. **10** illustrates a cross sectional view of an electromagnet **1000** directed toward the mLED device structures.

FIG. **11** illustrates a cross sectional view of the electromagnet surface of the electromagnet after making contact with an uppermost surface of each of the one or more mLED device structures.

FIG. **12**A illustrates the structure of FIG. **11** after immersing the substrate including the mLED device structures in a chemical solution.

FIG. **12**B illustrates the structure of FIG. **12**A after a partial chemical etch of the sacrificial layer.

FIG. **12**C illustrates the structure of FIG. **12**A after the sacrificial layer is fully removed.

FIG. **12**D illustrates the structure of FIG. **12**C after the electromagnet and the device structures are removed from the chemical solution.

FIG. **13** illustrates a cross sectional view following the placement of the mLED device structures depicted in FIG. **12**D, on an uppermost surface of an adhesion layer formed above an intermediate substrate.

FIG. **14**A illustrates the structure of FIG. **13** after the electromagnet is de-energized and removed from the vicinity of the mLED device structures.

FIG. **14**B illustrates a plan view of the structure in FIG. **14**A after the electromagnet has placed the mLED device structures onto an adhesion layer.

FIG. **15**A illustrates a cross sectional view of an electromagnetic apparatus directed towards an array of mLED device structures.

FIG. **15**B illustrates a cross sectional view of the structure of FIG. **15**A after a head structure of electromagnetic apparatus is in physical contact with an mLED device structure.

FIG. **15**C illustrates a cross sectional view of the structure of FIG. **15**B after the electromagnetic apparatus including the mLED device structure is raised.

FIG. **15**D illustrates a cross sectional view of the electromagnetic apparatus and the mLED device structure attached directed towards an adhesion layer on an assembly substrate.

FIG. **15**E illustrates a cross sectional view of the structure of FIG. **15**D after mLED device structure is placed on the adhesion layer.

FIG. **15**F illustrates a cross sectional view of the structure of FIG. **15**E following placement of the mLED device structure on the adhesion layer and removal of the electromagnetic apparatus.

FIG. **16**A is a cross-sectional illustration of a plurality of mLED structures formed on a sacrificial layer.

FIG. **16**B is a plan-view illustration of the structure of FIG. **16**A.

FIG. **17**A is a cross-sectional illustration of a plurality of mLED devices on an adhesion layer formed above an intermediate substrate.

FIG. **17**B is a plan-view illustration of the structure of FIG. **17**A.

FIG. **18**A is a cross-sectional illustration of a plurality of mLED structures on a sacrificial layer.

FIG. **18**B is a plan-view illustration of the structure of FIG. **18**A.

FIG. **19**A is a cross-sectional illustration of a plurality of mLED device on an adhesion layer formed above an intermediate substrate.

FIG. **19**B is a plan-view illustration of the structure of FIG. **19**A.

FIG. **20**A illustrates a cross sectional view of the structure of FIG. **15**F after the placement of a second mLED device structure adjacent to the mLED device structure.

FIG. **20**B illustrates a cross sectional view of the structure of FIG. **20**A after the placement of a third mLED device structure adjacent to the mLED device structure.

FIG. **20**C illustrates a cross sectional view of the structure of FIG. **20**B after the electromagnet is deactivated and raised.

FIG. **21** illustrates a plan-view depicting an arrangement of a first, a second and a third mLED device structure on an adhesion layer, in accordance with embodiments of the present disclosure.

FIG. **22**A illustrates a cross sectional view of an electromagnetic apparatus **600** directed towards a plurality of mLED device structures of a first type on an adhesion layer.

FIG. **22**B illustrates a cross sectional view of the structure of FIG. **22**A after each head structure in the plurality of head structures is in physical contact with a single mLED device structure of the first type.

FIG. **22**C illustrates a cross sectional view of the structure of FIG. **22**B after the electromagnetic apparatus, and the magnetically coupled mLED device structures of the first type are removed.

FIG. **22**D illustrates a cross sectional view of the structure of FIG. **22**C after the electromagnetic apparatus, and the magnetically coupled mLED device structures of the first type are directed towards an adhesion layer on an assembly substrate.

FIG. **22**E illustrates a cross sectional view of the structure of FIG. **22**D after the mLED device structures of the first type are placed on the adhesion layer.

FIG. **22**F illustrates a cross sectional view of the structure of FIG. **22**D after the electromagnetic apparatus is raised.

FIG. **23**A illustrates the structure of FIG. **22**D following the placement of an mLED device structure of a second type and a third mLED device structure of a third type adjacent to each of the mLED device of the first type structure using the electromagnetic apparatus.

FIG. **23**B illustrates a plan-view depicting a plurality of arrangements of mLED device structures including mLED device structures of the first, second and third type on an adhesion layer, in accordance with embodiments of the present disclosure.

FIG. **24** illustrates a flow diagram depicting a method to transfer mLED device structures from a native substrate to an assembly substrate in accordance with embodiments of the present disclosure.

FIG. **25** illustrates a computing device with machine-readable storage media that stores instructions for performing one or more methods to transfer mLED device structures from a native substrate to an assembly substrate, in accordance with some embodiments of the disclosure.

DESCRIPTION OF THE EMBODIMENTS

Electromagnetic apparatus and methods of fabrication are described. The disclosure described herein presents a new solution to the specific challenge of selectively picking and transferring micro-devices by implementing an electromagnetic apparatus that is tolerant to variations in the micro-device height. In the following description, numerous specific details are set forth, such as novel structural schemes and detailed fabrication methods, in order to provide a thorough understanding of embodiments of the present disclosure. It will be apparent to one skilled in the art that embodiments of the present disclosure may be practiced without these specific details. In other instances, well-known features, such as transistor operations and switching operations associated with embedded memory, are described in lesser detail in order to not unnecessarily obscure embodiments of the present disclosure. Furthermore, it is to be

understood that the various embodiments shown in the Figures are illustrative representations and are not necessarily drawn to scale.

In some instances, in the following description, well-known methods and devices are shown in block diagram form, rather than in detail, to avoid obscuring the present disclosure. Reference throughout this specification to "an embodiment" or "one embodiment" or "some embodiments" means that a particular feature, structure, function, or characteristic described in connection with the embodiment is included in at least one embodiment of the disclosure. Thus, the appearances of the phrase "in an embodiment" or "in one embodiment" or "some embodiments" in various places throughout this specification are not necessarily referring to the same embodiment of the disclosure. Furthermore, the particular features, structures, functions, or characteristics may be combined in any suitable manner in one or more embodiments. For example, a first embodiment may be combined with a second embodiment anywhere the particular features, structures, functions, or characteristics associated with the two embodiments are not mutually exclusive.

As used in the description and the appended claims, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will also be understood that the term "and/or" as used herein refers to and encompasses any and all possible combinations of one or more of the associated listed items.

The terms "coupled" and "connected," along with their derivatives, may be used herein to describe functional or structural relationships between components. It should be understood that these terms are not intended as synonyms for each other. Rather, in particular embodiments, "connected" may be used to indicate that two or more elements are in direct physical, optical, or electrical contact with each other. "Coupled" may be used to indicated that two or more elements are in either direct or indirect (with other intervening elements between them) physical or electrical contact with each other, and/or that the two or more elements co-operate or interact with each other (e.g., as in a cause an effect relationship).

The terms "over," "under," "between," and "on" as used herein refer to a relative position of one component or material with respect to other components or materials where such physical relationships are noteworthy. For example, in the context of materials, one material or material disposed over or under another may be directly in contact or may have one or more intervening materials. Moreover, one material disposed between two materials may be directly in contact with the two layers or may have one or more intervening layers. In contrast, a first material "on" a second material is in direct contact with that second material/material. Similar distinctions are to be made in the context of component assemblies. As used throughout this description, and in the claims, a list of items joined by the term "at least one of" or "one or more of" can mean any combination of the listed terms.

The term "adjacent" here generally refers to a position of a thing being next to (e.g., immediately next to or close to with one or more things between them) or adjoining another thing (e.g., abutting it).

The term "signal" may refer to at least one current signal, voltage signal, magnetic signal, or data/clock signal. The meaning of "a," "an," and "the" include plural references. The meaning of "in" includes "in" and "on."

The term "device" may generally refer to an apparatus according to the context of the usage of that term. For example, a device may refer to a stack of layers or structures, a single structure or layer, a connection of various structures having active and/or passive elements, etc. Generally, a device is a three-dimensional structure with a plane along the x-y direction and a height along the z direction of an x-y-z Cartesian coordinate system. The plane of the device may also be the plane of an apparatus which comprises the device.

Here, an in-plane magnet refers to a magnet that has magnetization in a direction substantially along the plane of the magnet. For example, a magnet with a magnetization which is in an x or y direction and is in a range of 0 (or 180 degrees)+/−20 degrees relative to an x-y plane of a device.

The term "free" or "unfixed" here with reference to a magnet refers to a magnet whose magnetization direction can change along its easy axis upon application of an external field or force (e.g., Oersted field, spin torque, etc.). Conversely, the term "fixed" or "pinned" here with reference to a magnet refers to a magnet whose magnetization direction is pinned or fixed along an axis and which may not change due to application of an external field (e.g., electrical field, Oersted field, spin torque).

As used throughout this description, and in the claims, a list of items joined by the term "at least one of" or "one or more of" can mean any combination of the listed terms. Unless otherwise specified in the explicit context of their use, the terms "substantially equal," "about equal" and "approximately equal" mean that there is no more than incidental variation between two things so described. In the art, such variation is typically no more than +/−10% of a predetermined target value.

The terms "left," "right," "front," "back," "top." "bottom," "over," "under," and the like in the description and in the claims, if any, are used for descriptive purposes and not necessarily for describing permanent relative positions. For example, the terms "over," "under," "front side," "back side," "top," "bottom," "over," "under," and "on" as used herein refer to a relative position of one component, structure, or material with respect to other referenced components, structures or materials within a device, where such physical relationships are noteworthy. These terms are employed herein for descriptive purposes only and predominantly within the context of a device z-axis and therefore may be relative to an orientation of a device. Hence, a first material "over" a second material in the context of a figure provided herein may also be "under" the second material if the device is oriented upside-down relative to the context of the figure provided. In the context of materials, one material disposed over or under another may be directly in contact or may have one or more intervening materials. Moreover, one material disposed between two materials may be directly in contact with the two layers or may have one or more intervening layers. In contrast, a first material "on" a second material is in direct contact with that second material. Similar distinctions are to be made in the context of component assemblies.

The term "between" may be employed in the context of the z-axis, x-axis or y-axis of a device. A material that is between two other materials may be in contact with one or both of those materials, or it may be separated from both of the other two materials by one or more intervening materials. A material "between" two other materials may therefore be in contact with either of the other two materials, or it may be coupled to the other two materials through an intervening material. A device that is between two other devices may be

directly connected to one or both of those devices, or it may be separated from both of the other two devices by one or more intervening devices.

In an embodiment, an electromagnetic apparatus that is capable of selectively removing large volumes of scaled micro-LED devices may enable higher adoption of mLED-based display technology. In particular, one aspect of micro-LED display technology involves transfer of mLED devices from the substrate, on which these where fabricated, onto a display matrix substrate that contains driving circuitry required to activate the mLEDs. Substrate bonding and transfer printing techniques are commonly used for some applications. However, selective micro transfer of mLED continues to be a challenge.

Since most materials of interest are challenging to "pick-up" in their as-grown form using currently available technology, one strategy to achieve "pickable" devices is to utilize engineered sacrificial layers underneath the device layers of interest. In spite of this, balancing the kinematics of the adhesion remains a practical problem that becomes even harder when normal variability in the manufacturing process of the micro-devices is considered.

In some embodiments, the micro-devices which are produced by a high-volume manufacturing process may have some intrinsic height variation, creating a challenge for tools that rely on, for example, electrostatic phenomenon to pick up the micro devices. Height variations may result in an air-gap between the tool performing the picking up and the micro-device. In some instances, a gap as small as 10 nm may introduce capacitance that can drastically increase the required applied voltage. In practice, existence of such air gap is expected due to allowed tolerances in the manufacturing process of the mLED devices that may result in height variation of up to several 100's of nanometers, corresponding to height variability in the order of +/−10%.

The embodiments of the present disclosure describe an electromagnetic apparatus that is tolerant to variations in the mLED device height and can selectively transfer mLED devices from a provider substrate to a host substrate while maintaining pattern fidelity. Depending on requirements, the electromagnetic apparatus may be customized making it suitable for small scale displays and for large area displays such as for TVs.

In accordance with an embodiment of the present disclosure, an electromagnetic apparatus includes a body structure having a non-magnetic material above a substrate. The body structure promotes the subsequent masking and selective growth of magnetic materials. The electromagnetic apparatus further includes at least one isolation structure including a dielectric material on a portion of the body structure. In one embodiment, the electromagnetic apparatus further includes a magnetic structure having two separate portions, one on each side of the isolation structure. A first magnetic structure portion extends from a first sidewall of the isolation structure onto an upper surface and on to a first sidewall of the body structure and a second magnetic structure portion extends from an opposite second sidewall of the isolation structure onto an upper surface and on to a second sidewall of the body structure (opposite to the first sidewall of the body structure). The magnetic structure does not extend over and is discontinuous over the isolation structure. Collectively, the isolation structure and a part of the first and the second magnetic structure portions that extend along the two opposing sidewalls of isolation structure is known as a head structure. The head structure is a non-moving component of the electromagnetic apparatus that comes in contact with mLED devices intended to be picked up and transferred from one substrate to another. The magnetic structure includes a material that has high permeability to collect and direct magnetic flux lines. The electromagnetic apparatus further includes an electromagnet on a side opposite to the isolation structure. The electromagnet is coupled with the magnetic structure and is a source of the magnetic flux lines when energized.

When the electromagnetic apparatus is brought in the vicinity of an mLED device and the electromagnet is energized, flux lines are directed into a path that goes from one magnetic structure portion on one side of the isolation structure through the mLED device into the second magnetic structure portion on an opposite side of the isolation structure. The presence of the discontinuity of magnetic material in the head structure increases reluctance for the magnetic flux lines, forcing them to pass through a magnetic material in the mLED device itself, which results in an electromagnetic force that picks up the micro-device from the designated substrate.

Depending on embodiments, the number of isolation structures may be varied from a single structure to several hundred thousand in an array, depending on the size of the mLED to be transferred. In the array, the isolation structures may be separated by a distance that depends on the size and density of the mLED devices in the provider or native substrate and on the density and pitch of the mLED devices in the host substrate.

FIG. **1**A illustrates a cross-sectional view of an electromagnetic apparatus **100**, in accordance with an embodiment of the present disclosure. The electromagnetic apparatus **100** includes a base structure **102** including a non-magnetic material above a substrate **118** and an isolation structure **106** including a dielectric, on a portion **102**A of the base structure **102**. The electromagnetic apparatus **100** further includes a structure **110** including a first sidewall portion **110**A adjacent to a first sidewall **106**A of the isolation structure **106** and above a portion **102**B of the base structure **102**. Sidewall portion **110**A of the structure **110** includes a magnetic material. Structure **110** further includes sidewall portion **110**B adjacent to sidewall **106**B, opposite to sidewall **106**A, of isolation structure **106**. As illustrated, sidewall portion **110**B is above portion **102**C of base structure **102**. Sidewall portions **110**A and **110**B of structure **110** and isolation structure **106**, as illustrated, are collectively referred to as head structure **112** (inside dashed lines). Electromagnetic apparatus **100** further includes electromagnet **122** below and coupled magnetically with magnetic material of structure **110**.

In an embodiment, structure **110** includes a magnetic material having one or more of: mu-alloy, perma-alloy, an alloy of iron and nickel, an alloy of nickel, and cobalt, or an alloy of nickel, cobalt and iron. Structure **110** is designed to confine magnetic flux from electromagnet **122** when electromagnetic apparatus **100** is operational. As such, the magnetic material of structure **110** is preferably of high magnetic permeability. In an embodiment, the magnetic material has a permeability greater than 50.

In an embodiment, sidewall portion **110**A has a width W_{M1}, defined by a distance along an X axis as illustrated in FIG. **1**A. Sidewall portion **110**B has a width W_{M2} along the X axis and isolation structure **106** has a width W_{IS} along the X axis. In an embodiment, the width of isolation structure **106**, W_{IS} is determined from the magnetic reluctance required for delivering the maximum electromagnetic force to the mLED. According to one embodiment, W_{IS} is comparable to W_{M1} or W_{M2}, such as is shown in the cross-sectional illustration of FIG. **1**A. The overall size of head W_S

is usually comparable to the size of mLED to be picked. In some embodiments, isolation structure **106** has a width W_{IS} that is between 5 nm and 20 micro-meters (microns). A width W_{IS} between 5 nm and 2 microns is less than a width of mLED devices that head structure **112** is designed to pick. In some embodiments, each of the widths W_{M1}, W_{M2} are between 10 nm and 5 microns. In some embodiments, width W_{IS} is between 20% to 30% of the combined total width of W_{M1}, W_{M2} and W_{IS}. Depending on embodiments, the combined total width of W_{M1}, W_{M2} and W_S is between 15 nm-60 microns. In an embodiment, isolation structure **106** includes a dielectric material having silicon and oxygen (e.g., SiO_2), silicon and carbon (e.g., SiC) or silicon and nitrogen (e.g., Si_3N_4). In other embodiments, isolation structure **106** includes carbon doped silicon oxide or even an airgap.

As head structure **112** is designed to mechanically contact an LED structure, it is advantageous for the top surface of the head structure to be substantially planar. As illustrated, top surfaces of sidewall portion **110**A, sidewall portion **110**B and isolation structure **106** are co-planar or substantially co-planar.

As illustrated, sidewalls **106**A and **106**B are vertical relative to planar surface **102**D of the base structure **102**. However, in other embodiments, the sidewalls **106**A and **106**B each have a slope that is less than 90 degrees relative to planar surface **102**D, such as is illustrated in FIG. **1**C. In one such embodiment, sidewall portions **110**A and **110**B are substantially conformal with sloped sidewalls **106**A and **106**B.

Referring again to FIG. **1**A, base structure **102** includes non-magnetic metal, such as but not limited to, copper, and tungsten or an alloy of these metals. Depending on the embodiment, base structure **102** has a thickness between 100 nm and 10000 nm. In an embodiment, base structure **102** has a width, WB that is substantially equal to the combined widths W_{M1}, W_{M2} and W_{IS}, as illustrated.

In an embodiment, substrate **118** includes a suitable material such as but not limited to, quartz, single crystal silicon, polycrystalline silicon and silicon on insulator (SOI). In another embodiment, substrate **118** includes other rigid or flex materials suitable for subsequent metal and dielectric deposition processes. In an illustrative embodiment, substrate **118** includes a layer of dielectric material above a semiconductor material, such as but not limited to, single crystal silicon, polycrystalline silicon, silicon germanium or a suitable group III-N or a group III-V compound.

In an embodiment, adhesion layer **114** is between substrate **118** and base structure **102**. In an embodiment, adhesion layer **114** includes a combination of nitrogen and one or more metals such as titanium, tungsten or tantalum (e.g., TiN, TaN). Adhesion layer **114** may have a thickness between 10 nm and 100 nm.

In an embodiment, electromagnet **122** generates magnetic flux of desired intensity to deliver needed force to selectively pick one or more designated mLEDs.

FIG. **1**B illustrates an isometric view of electromagnetic apparatus **100**. In an illustrative embodiment, electromagnetic apparatus **100** has a block structure. Electromagnetic apparatus **100** has length, L_1, along the Y-axis that is determined by the corresponding dimension on the mLED device to be picked up.

FIG. **2**A illustrates a cross-sectional view of electromagnetic apparatus **200**, in accordance with an embodiment of the present disclosure. The electromagnetic apparatus further includes isolation structure **206** on body structure portion **202**A. Electromagnetic apparatus **200** further includes magnetic structure **210**. Magnetic structure **210** includes first magnetic structure **210**A adjacent to sidewall **206**A of isolation structure **206**. Magnetic structure **210**A extends continuously onto body structure portion **202**B and adjacent to sidewall **202**D of body structure **202**. Magnetic structure **210**A is also above body structure portion **202**F that extends beyond sidewall **202**D, as illustrated in FIG. **2**A. Magnetic structure **210** includes second magnetic structure **210**B adjacent to sidewall **206**B opposite to sidewall **206**A. Magnetic structure **210**B extends continuously onto body structure portion **202**C and adjacent to sidewall **202**E of body structure **202**. Magnetic structure **210**A is also above body structure portion **202**G, that extends beyond sidewall **202**E, as illustrated in FIG. **2**A. As illustrated, isolation structure **206** and portions of magnetic structure **210**A and **210**B adjacent to isolation structure **206** are collectively referred to as head structure **212** (inside dashed lines). Electromagnetic apparatus **200** further includes electromagnet **122** coupled with magnetic structure **210**.

Magnetic structure **210**A adjacent to sidewall **202**D has a thickness, T_B. In an embodiment, thickness, T_B is substantially similar to thickness T_{M1}, of magnetic structure **210**A on body structure portion **202**B. In an embodiment, thickness, T_{M1} is same or substantially same as width, W_{M3}, of magnetic structure **210**A adjacent to sidewall **206**A.

Magnetic structure **210**B, adjacent to sidewall **202**E has thickness, T_B. In an embodiment, thickness, T_B, is substantially similar to thickness, T_{M2} of magnetic structure **210**B on body structure portion **202**C. In an embodiment, T_{M1} is same or substantially same as width, W_{M4}, of magnetic structure **210**B adjacent to sidewall **206**B.

In an embodiment, the width W_{M3} and W_{M4} are equal or substantially equal to balance a magnetic flux generated through magnetic structure **210** when electromagnet **122** is operational. Similarly, T_{M1} and T_{M2} are equal or substantially equal to balance magnetic flux through magnetic structure **210**. A balanced magnetic flux through magnetic structures **210**A and **210**B can provide mechanical stability when electromagnetic apparatus **200** is utilized to pick up mLED devices during operation.

In an embodiment, head structure **212** has height, H_{HS}, and body structure **202** has height, H_B. As illustrated head structure **212** has height, H_{HS} that is less than height H_B, of body structure **202**. The height, $(H_{HS}-T_{M2})$ may be equal to approximately half a thickness of an mLED device to be picked by head structure **112**.

In an illustrative embodiment, head structure **212** has width W_{HS}, that is less than length L_B of body structure **202**. Width W_{HS} may be designed to be similar or substantially similar to width of an mLED device to be picked during operation.

In other embodiments body structure **202** may have length L_B, to accommodate a plurality of head structures each resembling head structure **212** and having one or more features such as width W_{HS}, height H_{HS} and length L_{HS} of head structure **212**, as will be described in FIG. **4**A below.

In one embodiment, thickness of magnetic portion T_B is preferably much larger than thickness H_{HS} allowing for confining larger portion of the magnetic flux lines parallel to direction L_B. In an embodiment, magnetic structure **210**B includes a material that is same or substantially same as a material of magnetic structure **210**A. In such an embodiment, magnetic structure **210**A and **210**B each include a material that is same or substantially same as magnetic material of sidewall portion **110**A.

FIG. **2**B illustrates an isometric view of the electromagnetic apparatus **200**. In the illustrative embodiment, the head structure **112** has a length, L_{HS}, along a Y-axis. As illus-

trated, top surface **210**AA of the magnetic structure **210**A, adjacent to the sidewall **206**A, top surface **210**BA of the magnetic structure **210**B, adjacent to the sidewall **206**B, and a top surface **206**C of the isolation structure **206** are co-planar or substantially co-planar.

Also, as shown in FIG. **2**B, magnetic structures **210**A and **210**B are not physically connected anywhere in electromagnetic apparatus **200**. In an embodiment, magnetic structures **210**A and **210**B are separated by an amount equivalent to width W_1 of isolation structure **206** along length, L_{HS} of head structure **212**. The presence of isolation structure **206** introduces a discontinuity in magnetic material between magnetic structure **210**A and **210**B and creates a large magnetic reluctance when electromagnet **122** is energized. The magnetic reluctance is designed to be sufficiently large to force magnetic flux generated by operational electromagnet **122** to pass from one magnetic structure (e.g., **210**A) to another magnetic structure (e.g., **210**B) through mLED when a top surface of head structure **112** is positioned adjacent to an mLED device.

FIG. **3**A illustrates a cross-sectional view of electromagnetic apparatus **300** in accordance with an embodiment of the present disclosure. In an embodiment, electromagnetic apparatus **300** includes encapsulation **302** on the structure of electromagnetic apparatus **300** described in association with FIGS. **2**A and **2**B.

In the illustrative embodiment, encapsulation **302** is on a top surface of isolation structure **206**, on exposed surfaces of magnetic structure **210**A and **210**B, on sidewalls of body structure portions **202**F and **202**G, on sidewalls **114**A and **114**B of adhesion layer **114** and on sidewalls **118**A and **118**B of substrate **118**. In an embodiment, encapsulation **302** includes a hermetic dielectric material such as silicon nitride, or silicon carbide. Encapsulation **302** protects the various layers and structures of electromagnetic apparatus **200** from an external environment during operation and has a thickness between 5 nm and 20 nm. In some embodiments (not illustrated), encapsulation **302** is also between substrate **118** and the electromagnet **122**.

FIG. **3**B illustrates an isometric view of electromagnetic apparatus **300** depicted in FIG. **3**A. In the illustrative embodiment, encapsulation layer **302** is adjacent to all exposed faces of electromagnetic apparatus **200** but excludes electromagnet **122**. In the illustrative embodiment, a cut out in encapsulation layer **302** illustrates a portion of electromagnetic apparatus **200**.

FIG. **4**A illustrates a cross sectional view of electromagnetic apparatus **401**A with an array of extruded heads, in accordance with embodiments of the present disclosure. Electromagnetic apparatus **401**A includes body structure **402** having a non-magnetic material, isolation structure **406** including a dielectric material on body structure portion **402**A. Isolation structure **408** including the dielectric material is on body structure portion **402**D as illustrated. Electromagnetic array **401**A further includes magnetic structure **410** that has one or more features of magnetic structure **210**. For example, magnetic structure **410** includes magnetic structure portion **410**A adjacent to isolation structure sidewall **406**A, magnetic structure portion **410**A extends continuously onto body structure portion **402**B, and adjacent to body structure sidewall **402**F. Magnetic structure **410** includes magnetic structure portion **410**B adjacent to isolation structure sidewall **408**A, where magnetic structure portion **410**B extends continuously onto body structure portion **402**C and adjacent to body structure sidewall **402**G. Electromagnetic array **401**A further includes magnetic structure portion **410**C adjacent to isolation structure sidewall **406**B and adjacent to isolation structure sidewall **408**B. Magnetic structure portion **410**C extends onto body structure portion **402**E, continuously between isolation structure sidewalls **406**B and **408**B. In an embodiment, magnetic structure portions **410**A, **410**B and **410**C include same material as the material of magnetic structure **210**A and **210**B.

As illustrated, isolation structure **406**, and magnetic structure portions **410**A and **410**C adjacent to isolation structure sidewalls **406**A and **406**B are collectively referred to as head structure **412** (inside dashed lines). Head structure **412** has one or more features of head structure **212** such as having width W_{12}, and height H_{12} that is same or substantially same as width W_{HS}, and height, H_{HS}, of head structure **212**. In some embodiments head structure **412** is separated from head structure **414** in electromagnetic apparatus **401**A by width S_{H12}.

As illustrated, isolation structure **408**, and magnetic structure portions **410**C and **410**B adjacent to isolation structure sidewalls **408**B and **408**A are collectively referred to as head structure **414** (inside dashed lines). Head structure **414** has one or more features of head structure **212** such as having width W_{14}, and height H_{14}, that is same or substantially same as width W_{HS}, and height H_{HS}, of head structure **212**.

The relative size of widths and heights of head structures **412** and **414** may depend on the size of the micro device to be picked up. In an embodiment, head structures **412** and **414** have width W_{12} and W_{14}, respectively and height H_{12} and H_{14}, respectively, that are all same or substantially same.

Head structures **412** and **414** each have height H_{12} and H_{14}, respectively, that is greater than sum of thicknesses, T_{MM}, of magnetic material **410** and approximately half a thickness of mLED devices (not shown) that head structures **412**, and **414** are designed to pick from a substrate (to be discussed in FIG. **7**).

In an embodiment, body structure **402** includes a material that is same or substantially same as material of body structure **202**. In an embodiment, isolation structures **406** and **408** each include a material that is same or substantially same as the material of isolation structure **206**.

FIG. **4**B illustrates an isometric view of electromagnetic apparatus **400**, in accordance with embodiments of the present disclosure. In an illustrative embodiment, electromagnetic apparatus **400** includes a first electromagnetic array **401**A (described in FIG. **4**A) and second electromagnetic array **401**B, where first electromagnetic array **401**A and second electromagnetic array **401**B are magnetically coupled when electromagnetic apparatus **400** is energized.

In an illustrative embodiment, electromagnetic array **401**B includes one or more structural embodiments of the electromagnetic array **401**A such as a plurality of head structures such as head structures **412** and **414** (inside dashed lines), the body structure **402**, magnetic structure portions **410**A, **410**B and **410**C. In an illustrative embodiment, head structure **412** in electromagnetic array **401**B has width W_{12}, length L_{12}, and height H_{12} that is same or substantially same as width W_{12}, length L_{12}, and height, H_{12} of head structure **412** in electromagnetic array **401**A. In an illustrative embodiment, head structure **414** in electromagnetic array **401**B has width W_{14}, length L_{14}, and height, H_{14} that is same or substantially same as width W_{14}, length L_{14}, and height, H_{14} of head structure **414** in electromagnetic array **401**A.

In an illustrative embodiment, electromagnetic arrays **401**A and **401**B share body structure **402** but magnetic structure **410** of electromagnetic array **401**B is separated from magnetic structure **410** of electromagnetic array **401**A

by dielectric layer **420**. Dielectric layer has width W_{AB} (along the Y-direction as shown). The width W_{AB} may depend on the spatial arrangement of the mLEDs on a provider substrate and on a desired spatial arrangement of a receiving substrate.

In some embodiments, head structure **412** in electromagnetic array **401**A is aligned with head structure **414** in electromagnetic array **401**B. For example, in an illustrative embodiment, head structure **412** in electromagnetic array **401**A is aligned with head structure **414** in electromagnetic array **401**B along the X-axis, but separated along an orthogonal direction, such as along a Y-axis. Head structure **412** in electromagnetic array **401**A is on same plane as head structure **414** in electromagnetic array **401**B. In some such embodiments, head structure **412** is also separated from head structure **414** in electromagnetic array **401**B by width S_{H12}.

In an illustrative embodiment, magnetic structure **418**A adjacent to dielectric layer **420** couples magnetic structure portion **410**A of the electromagnetic array **401**B with the magnetic structure portion **410**A of electromagnetic array **401**A. Second magnetic structure **418**B couples magnetic structure portion **410**B of electromagnetic array **401**B with magnetic structure portion **410**B of electromagnetic array **401**A. Electromagnet **122** couples each of magnetic structures **410** in electromagnetic arrays **401**A and **401**B. In an illustrative embodiment, head structures **412**, and **414** are simultaneously capable of magnetically coupling mLED devices when electromagnet **122** is energized.

In an embodiment, adhesion layer **114** and substrate **118** is shared between arrays **401**A and **401**B as illustrated in FIG. 4B.

FIG. **4**C illustrates an isometric view of electromagnetic apparatus **400**B including a plurality of operable electromagnetic arrays **401**A and **401**B, in accordance with an embodiment of the present disclosure. In an illustrative embodiment, electromagnetic array **401**A includes electromagnet **422**A and the array **401**B includes an electromagnet **422**B. Electromagnet **422**A may be operated in tandem or independently of electromagnet **422**B.

In an illustrative embodiment, electromagnetic arrays **401**A and **401**B are separated from each other by distance SAB. Distance SAB may be governed by spatial distribution of mLEDs targeted for pick and/or placement and strength of electric current used to energize the electromagnet.

As shown, adhesion layer **114** is uncoupled between first electromagnetic array **401**A and second electromagnetic array **401**B. In an illustrative embodiment, adhesion layer **114** is separated by dielectric layer **420**.

In FIGS. **4**A-**4**C, although two head structures are illustrated, electromagnetic apparatus can have as many as 100,000 or more in a single array.

FIG. **5** illustrates a flow diagram depicting a method **500** to fabricate an electromagnetic apparatus with one or more features of electromagnetic apparatus **401**A. Method **500** begins at operation **510** by forming a body structure above a substrate, where the body structure has a base structure and a core structure on a portion of the base structure. The method continues at operation **520** with a selective formation of a first layer of magnetic material on the base structure and on sidewalls of the core structure. Method **500** then continues at operation **530** with formation of a plurality of isolation pillars on the core structure. Method **500** continues at operation **540** with formation of a second layer of magnetic material on the body structure, adjacent to a portion of each of the plurality of isolation pillars and on a portion of the first layer of magnetic material. The method concludes at operation **550** with formation of a third layer of magnetic material on each of the sidewalls of the plurality of isolation pillars, and on portions of the second layer of magnetic material.

FIG. **6**A illustrates adhesion layer **114** formed above substrate **118** and seed layer **602** formed above adhesion layer **114**.

The adhesion layer **114** provides strong bonding between the substrate **118** and the seed layer **602**. In an embodiment, adhesion layer **114** is deposited to a thickness between 10 nm and 100 nm. In some embodiments adhesion layer **114** is deposited using a chemical vapor deposition process or plasma enhanced chemical vapor deposition process.

In an embodiment, seed layer **602** includes a metal or a metal alloy, such as but not limited to copper, tantalum, ruthenium or tungsten. In an embodiment, seed layer **602** is not magnetic and is a metal that is adequate for subsequent electroplating process of both magnetic and non-magnetic materials originating from this layer. In some embodiments seed layer **606** is deposited using a physical sputter deposition process.

FIG. **6**B illustrates a cross-sectional view of the structure in FIG. **6**A following the formation of mask **604** on the seed layer **602**. In an embodiment, mask **604** defines shape, size and location of a bulk structure, which is to be subsequently formed. In an illustrative embodiment, mask **604** defines opening **605** where a bulk structure is to be subsequently formed.

In some embodiments, mask **604** is formed by a lithographic process. In other embodiments, mask **604** includes a dielectric material that has been patterned. The height of mask **604** may depend on how much spatial buffer is required for separating substrate **118** from a head structure to be subsequently formed. In some embodiments, practical height of mask **604** ranges between 100 nanometers to 3 micrometers.

FIG. **6**C illustrates a cross-sectional view of the structure in FIG. **6**B following the formation of non-magnetic material **610** in the opening **605**, on a portion of seed layer **602**. Non-magnetic material **610** forms a bulk core of electromagnetic apparatus being fabricated. Non-magnetic material **610** may include a material such as but not limited to copper, tantalum, ruthenium, or tungsten. In other embodiments, non-magnetic material **610** may include a material that is different from seed layer **602**.

In an embodiment, non-magnetic material **610** is formed using electroplating or electroless plating process, if it is a non-magnetic metal or metal alloy. In an embodiment, non-magnetic material **610** conforms to sidewalls **604**A and **604**B of mask **604**. In the illustrative embodiment, sidewalls **604**A and **604**B are vertical or substantially vertical and non-magnetic material **610** has sidewalls **610**A and **610**B that are vertical or substantially vertical as deposited.

Uppermost surface **610**C of the non-magnetic material **610** may be planar or substantially planar as deposited. Further processing may be required to achieve desired planarity as will be discussed further below.

FIG. **6**D illustrates the structure of FIG. **6**C following removal of mask **604** followed by formation of mask **612** on non-magnetic material **610**. In an embodiment, mask **604** (not shown) is removed by a wet chemical process selective to seed layer **602** and nonmagnetic material **610**. In an embodiment, wet chemical process does not react with non-magnetic material **610**, and sidewalls **610**A and **610**B remain substantially unaltered as deposited. As shown, uppermost surfaces **606**A and **606**B of seed layer **602** are also unaffected by the wet etch. After removal of mask **604**,

seed layer **602** and non-magnetic material **610** form a body structure such as body structure **202** (described in association with FIG. **2**A).

In an embodiment, second mask **612** is formed on uppermost surface **610**C. Sidewalls **610**A and **610**B and uppermost surfaces **606**A and **606**B remain exposed after formation of mask **612**. In an embodiment, mask **612** is formed by lithographic techniques.

FIG. **6**E illustrates the structure of FIG. **6**D following formation of magnetic material **616** on body structure **202**. In an embodiment, magnetic material **616** is formed on uppermost surfaces **606**A and **606**B and adjacent to sidewalls **610**A and **610**B of body structure **202**. In an embodiment, magnetic material **616** is deposited using electroplating or electroless deposition process. In an embodiment, magnetic material **616** includes a material that is t same or substantially same as the material of magnetic structure **210**. In an illustrative embodiment, sidewalls **610**A and **610**B of body structure **202** are vertical or substantially vertical and resultant sidewalls **616**A and **616**B of magnetic material **616** are formed vertically or substantially vertically guided by sidewalls **610**A and **610**B. Vertical regions, such as sidewalls **616**A and **616**B, may readily confine magnetic flux lines generated by an electromagnet that will be subsequently coupled with magnetic material **616**.

As shown, magnetic material **616** has uppermost surfaces **616**C and **616**D that are on a plane that is higher than a plane defining surface **610**C of the body structure **202**. In such an embodiment, magnetic material **616** and body structure **202** may be planarized in a subsequent operation.

FIG. **6**F illustrates the structure of FIG. **6**E following removal of mask **612** and planarization of upper portions of body structure **202** and top portions of magnetic material **616**. In an embodiment, mask **612** is removed using a process similar to the process utilized to remove mask **604**. In one such embodiment, mask **612** is removed selectively to magnetic material **616** and body structure **202**. After removal of mask **612**, body structure **202** and magnetic material **616** may be planarized. In an embodiment, the planarization process includes a chemical-mechanical polish (CMP) process. A CMP process may planarize the upper portions of body structure **202** and magnetic material **616** such that uppermost surfaces **616**C and **616**D are co-planar or substantially co-planar with uppermost surface **610**C of body structure **202**. Planar uppermost surface **610**C may help to reduce variability in heights of head structures that will be subsequently formed.

FIG. **6**G illustrates the structure of FIG. **6**H following formation of a plurality of isolation structures on surface **610**C of the body structure **202**. In an embodiment, a dielectric layer **620** is deposited on surface **610**C and on magnetic material **616**. In an embodiment, the dielectric material (indicated by the dashed lines **620**) includes a material such as silicon oxide, silicon nitride, carbon doped oxide, polyimide, spin-on-glass or carbon doped nitride. In an embodiment, mask is formed on the dielectric material and the dielectric material is subsequently patterned to form one or more isolation structures. The dielectric material may be deposited to a thickness that is greater than a final height of the isolation structure to accommodate losses from downstream processing (e.g., from planarization). In an embodiment, the patterning is performed using a plasma etch process. The plasma etch process may be highly anisotropic to produce isolation structures **620**A, **620**B and **620**C having vertical or substantially vertical sidewalls. In another embodiment, the isolation structures **620**A, **620**B and **620**C is directly formed using a photo-imageable polyimide (PIPI) that is deposited and patterned without the need for an etch process.

In the illustrative embodiment, three isolation structures **620**A, **620**B and **620**C are shown. The spacing between each isolation structure is governed by a thickness of the magnetic material to be formed adjacent to the isolation structure in a subsequent operation as well as by the size and spacing of mLED structures to be picked up from an external substrate.

FIG. **6**H illustrates the structure of FIG. **6**G following formation of second magnetic material **622** on magnetic material **616** and on portions of body structure **202**. In an illustrative embodiment, magnetic material **622** includes magnetic material portions **622**A and **622**D that are formed above magnetic material portions **616**E and **616**F respectively. As shown, magnetic material portions **622**B and **622**C are formed on body structure **202**. Portions of magnetic material portions **622**D and **622**C are also formed on body structure **202**. In an embodiment, magnetic material **622** is deposited to a thickness equivalent to one fourth to one half of the height of the mLED, corresponding to a thickness between 1 micrometer to 3 micrometers. As shown, magnetic material **622** has thickness, T_{MM}, that is less than height H_{ISO}, of isolation structures **620**A, **620**B or **620**C.

In an embodiment, magnetic material **622** includes a material that is same or substantially same as the magnetic material **616**. In other embodiments, the magnetic material **622** may include a material that is different from the magnetic material **616**.

FIG. **6**I illustrates the structure of FIG. **6**H following the formation of a third mask **624** on the magnetic material **622**. The mask includes openings **625**A and **625**B adjacent to each isolation structure **620**A, **620**B and **620**C. Each of the openings **625**A and **625**B is designed to have a width, W_O, that determines a width of a third magnetic material region to be formed in a subsequent operation. In an embodiment, mask **624** includes a material that is same or substantially same as the material of mask **612**, such as a photoresist or PIPI.

FIG. **6**J illustrates the structure of FIG. **6**I following the formation of a third magnetic material **626** selectively on magnetic material **622** in each of openings **625**A and **625**B. In an embodiment, magnetic material **626** is deposited by an electroplating or electroless deposition process and includes a material that is same or substantially same as the material of magnetic material **622**. In an illustrative embodiment, magnetic material **626** is formed in each of openings **625**A and **625**B, on magnetic material **622** adjacent to each isolation structure **620**A, **620**B and **620**C. It is to be appreciated that magnetic material **626** may be separated by isolation structures **620**A, **620**B and **620**C.

FIG. **6**K illustrates the structure of FIG. **6**J following the removal of mask **624** selective to magnetic material **626**, and each isolation structure **620**A, **620**B and **620**C.

FIG. **6**L illustrates the structure of FIG. **6**K following the formation of an encapsulation layer **632** on electromagnetic apparatus **600**. In an illustrative embodiment, encapsulation layer **632** is deposited conformally on head structures **630**A, **630**B and **630**C, on magnetic material **622** and on sidewalls of magnetic material **616**. Encapsulation layer **632** is designed to protect electromagnetic apparatus **600** from wear and from an external environment during use. In an embodiment, encapsulation layer **632** includes a hermitic material such as silicon nitride. Other hermetic, insulating and non-magnetic materials such as silicon carbide may also

be used. Encapsulation layer **632** may be deposited to a thickness between 10 nm-30 nm.

FIG. **7** illustrates a cross sectional view of electromagnetic apparatus **600** in close proximity to a plurality of mLED devices **700** on a substrate **712**. In an embodiment, electromagnetic apparatus **600** is well-aligned to the mLED devices **700** directly placed below head structures **630**A, **630**B and **630**C designed to be picked up from substrate **702** by a magnetic force.

In an illustrative embodiment, head structure **630**A is distant from head structure **630**B by spacing, W_{SHS}. Spacing W_{SHS} is designed based on spacing, W_S between mLED devices **700** and the size of mLED, W_{MD}.

Head structures **630**A, **630**B and **630**C each have width W_{HS}, and each mLED device **700** has width W_{MD}. In an illustrative embodiment, W_{HS} is equal or substantially equal to W_{MD}.

In an embodiment, spacing, W_{SHS}, between head structures may be related to width, W_{MD}, and spacing, W_S, between each successive mLED device **702** by relation [1]:

$$W_{SHS}=n\ W_{MD}+[n+1]W_S \quad [1]$$

where "n" is the number of mLED devices **700** to be skipped during the pick-up process of adjacent mLEDs. In an illustrative embodiment, where n=1, apparatus **600** will pick-up only every other mLED. In some such embodiments, spacing between each successive head structure, W_{SHS} is equal to W_{MD}+2 W_S. In an embodiment, when W_{MD} is equal to or substantially equal to spacing W_S, between each successive micro-device **702**A and **702**B, then W_{SHS} is equal to 3 W_{MD}. In an illustrative embodiment, W_{MD} is greater than spacing W_S.

In an embodiment, head structures **630**A, **630**B, **630**C each have height, T_H, which is greater than at least half a thickness, T_{MD}, of micro-device **702**. In one such embodiment, damage during operation of electromagnetic apparatus **600** may be prevented when thickness T_H, is greater than tolerances allowed for mLEDs thickness.

Electromagnetic apparatus **600** relies on employing discontinuity in magnetic flux across each head structure **630**A, **630**B, and **630**C for its operation, as will be described further below. Substrate **702** may include a material that is same or substantially same as material of substrate **118**. Intermediate layers may be present between mLED devices **700** and substrate **702**, as will be discussed below.

In an embodiment, a large collection of mLED devices, including mLED devices **700** are first fabricated on a provider or a native substrate that is unique to the desired color emitted by mLED device. The process of fabricating the mLED device utilizes known methodology. In an embodiment of the present disclosure, a ferromagnetic layer is usually deposited on the mLED device during its fabrication, as part of the interconnect structures needed to supply power from external source to the mLED for its operation. The existence of this ferromagnetic material on an mLED device provides for continuity of magnetic flux across each head structure **630**A, **630**B, and **630**C, when electromagnetic apparatus **600** is operational.

In one embodiment, the mLED devices undergo at least two transfer processes to be employed in an mLED-based display product. A first transfer process includes removing mLED devices of a single color (type) from a native substrate and placing them on an intermediate substrate. To enable the first transfer process, a sacrificial layer is deposited on the native substrate prior to the epitaxial deposition process required to fabricate the active area of the mLED. The sacrificial layer must be compatible with the epitaxial growth process utilized in forming the mLED. An example of such sacrificial layer is AlN. In an embodiment, the first transfer process relies on magnetically coupling the mLED devices to a bulk electromagnet, while chemically etching the sacrificial layer that bonds the mLED device structures to the native substrate. An activated bulk electromagnet may maintain spatial separation between mLED device structures, during the chemical etch process and during a subsequent transfer to an intermediate substrate. Once the mLED device structures are released from the native substrate, they are transported by the bulk electromagnet to be placed onto an adhesion layer, of known quantifiable adhesion properties, above the intermediate substrate. After the mLED device structures are placed on the adhesion layer, the bulk electromagnet is deactivated and the mLED device structures adhere to the adhesion layer. The bulk electromagnet may be different from the electromagnetic apparatus described above. The significance of the first transfer process is to provide the second transfer with known uniform adhesion between the mLEDs and the electromagnetic apparatus to enable robust transfer.

A second transfer process includes picking the mLED device structures from the intermediate substrate and placing them on an assembly substrate that is physically separate from the intermediate substrate. The second transfer utilizes the electromagnetic apparatus to magnetically couple a selection of mLED device structures that matches a pattern of head structures in the electromagnetic apparatus. The ferromagnetic material in the mLED device structures provides a path for flux continuity when the electromagnetic apparatus is activated. The electromagnetic apparatus is designed to deliver enough force to release the mLEDs from the intermediate substrate. Thus, the electromagnetic apparatus only picks mLED device structures that are substantially directly under the head structure.

In an embodiment, the size of the head structures, and the spacing between the head structures can be tailored to meet the size and spatial distribution of the mLED device pattern intended to be realized on the assembly substrate (second transfer process).

The first and second transfer process may be repeated for different mLED device structures so that the assembly substrate can assemble different types of mLED device structures in various configurations. In an exemplary embodiment, mLED device structures of three different colors to be placed on a common assembly substrate to form a pixel, each have same or substantially same size and relative spacing between adjacent mLED device structures. It is to be appreciated that a relative spacing between mLED device structures of a given color are preserved throughout the second transfer process.

FIGS. **8** through **13** describe a method to enable bulk transfer of a large collection of mLEDs of a single device type (for e.g., red, blue or green mLED) from a native substrate to an intermediate substrate.

FIG. **8** is a cross-sectional illustration of a plurality of devices such as mLED **804** above layer **802** formed above substrate **800**. Depending on embodiments, mLED **804** may include a single device type such as blue, red or green mLED. mLED **804** is fabricated using known techniques above substrate **802**. In an embodiment, layer **802** includes a sacrificial material such as aluminum nitride which is compatible with epitaxial growth process, essential for fabrication of mLED **804**, while is also removable by wet etch process during the first transfer process. Layer **802** may have a thickness between 20 nm to 500 nm.

FIG. **9**A is a cross-sectional illustration of the structure of FIG. **8** following formation of cap **806** including a ferromagnetic material, on each mLED **804**. The combination of cap **806** and mLED **804** is referred to as mLED device structure **810**. In an embodiment, cap **806** includes a ferromagnetic metal such as Co, Ni, Fe, or alloys of magnetic metals such as Co, Ni, Fe, or alloys thereof. In an embodiment, cap **806** has a thickness between 100 nm to 2 micrometers. For practical considerations, cap **806** is likely to be already accounted for during the formation of the interconnects needed to conduct power from an external source to the mLED device. In an embodiment, a combination of physical sputtering, electro and electroless plating techniques can be utilized.

FIG. **9**B is a plan-view illustration of the structure of FIG. **9**A. An array including a plurality of mLED device structures **810** are depicted. In the illustrative embodiment, mLED device structures **810** have a circular plan view profile. In other embodiments, mLED device structures **810** can have a rectangular plan view profile.

After fabrication of the plurality of mLED device structures **810**, a series of operations are performed to transfer a plurality of mLED device structures **810**. The transfer operation begins as illustrated in FIG. **10**.

FIG. **10** illustrates a cross sectional view of electromagnet **1000** directed in the negative Z direction (as denoted by arrow **1001**) toward mLED device structures **810**. The electromagnet has electromagnet surface **1000**A that will subsequently make contact with uppermost surface **806**A of mLED device structures **810**.

FIG. **11** illustrates a cross sectional view of electromagnet surface **1000**A of electromagnet **1000** after making contact with uppermost surface **806**A of each mLED device structure **810**. Electromagnet **1000** will exert a force to attract mLED device structures **810** to electromagnet surface **1000**A. In an embodiment, the electromagnet provides enough force to overcome variability in mLED height introduced during the manufacturing process. All mLEDs are coupled to the electromagnet.

FIG. **12**A illustrates the structure of FIG. **11** after immersing in chemical solution **1200** held in housing **1202**. In an embodiment, mLED device structures **810** and layer **802** are fully immersed in solution **1200**. In an illustrative embodiment, electromagnet **1000** is also partially immersed in solution **1200** such that electromagnet surface **1000**A is in solution **1200**. Solution **1200** is chosen to chemically react with and dissolve layer **802**, but not with mLED device structures **810**. Experts in the art recognize the need to apply a sheath or layer of protective material on the electromagnet itself to protect from wet etch while immersed.

FIG. **12**B illustrates the structure of FIG. **12**A after a partial chemical etch of layer **802**. The chemical solution will depend on the material of layer **802**. Electromagnet **1000** will continue to hold mLED device structures **810** through magnetic force while chemical solution **1200** etches layer **802**. In an illustrative embodiment, substrate **800** is supported (by a stand, not shown) to prevent unwanted stress on layer **802** during the chemical etch process.

FIG. **12**C illustrates the structure of FIG. **12**A after layer **802** is removed. The magnetic force will continue to hold mLED device structures **810** after layer **802** is etched.

FIG. **12**D illustrates the structure of FIG. **12**C after electromagnet **1000** and device structures **810** are removed from the chemical solution. In an embodiment, mLED device structures **810** are rinsed and dried. In an embodiment, when mLED device structures **810** are rinsed and dried, the spatial position between mLED device structures **810** is maintained.

FIG. **13** illustrates a cross sectional view following the placement of mLED device structures **810**, removed from chemical solution **1200** in FIG. **12**D, onto uppermost surface **1302**A of adhesion layer **1302** formed above intermediate substrate **1300**. In an embodiment, adhesion layer **1302** includes a material such as adhesion tape, commonly used in the packaging industry. The adhesion tape will have known adhesion characteristics, which is then used to determine force needed to release the mLED devices during the second transfer process. In an embodiment, adhesion layer **1302** includes a UV light-sensitive material. During pick-up phase of the mLED transfer process, adhesion layer **1302** may be exposed to UV radiation (not shown on FIG. **13**) to reduce the adhesion force between adhesion layer **1302** and the mLED, resulting in more degree of freedom in controlling the electromagnetic force needed to detach the mLED.

In an embodiment, mLED device structures **810** have same or substantially same height, T_{MD}. In one such embodiment, lowermost surface **804**A of mLED device structures **810** come into contact with uppermost surface **1302**A of adhesion layer **1302**, when electromagnet **1000** is lowered towards substrate **1300**, as shown in FIG. **13**.

FIG. **14**A illustrates the structure of FIG. **13** after electromagnet **1000** is de-energized and removed from the vicinity of mLED device structures **810**. In an embodiment, the adhesive force between uppermost surface **1302**A of adhesion layer **1302** and mLED device structures **810** enables mLED device structures **810** to remain after electromagnet **1000** is removed.

Once mLED device structures **810** are moved onto an intermediate substrate having an adhesion layer such as adhesion layer **1302**, one or more mLED device structures **810** may be moved onto an assembly substrate. In the aforementioned discussion, mLED device structures **810** belong to a single type of LED. The method to move LEDs of different colors may be the same as the method described above. In one embodiment, a lapping process of native substrates may be utilized to release mLED devices when inserting a sacrificial layer between the native mLED substrate and mLED devices is not practically feasible. In one such embodiment, electromagnet **1000** provides a strong holding force that maintains spatial distribution of mLEDs during the lapping process. In another embodiment, a combination of lapping and wet etch processes may be used to detach mLEDs from their native substrate. The magnetic force, provided by electromagnet **1000**, can maintain spatial distribution of the mLEDs.

FIG. **14**B illustrates a plan view of the structure **1400** in FIG. **14**A after electromagnet **1000** has placed mLED device structures **810** onto adhesion layer **1302**. In an embodiment, X and Y spacing, W_{LX}, and W_{LY}, respectively, between mLED device structures **810** are maintained relative to native substrate **800**, as illustrated. The method to assemble LEDS of different colors, for example, blue, red or green onto a common assembly substrate utilizes one or more of the electromagnetic apparatus described in association with FIGS. **2**-**4**.

In an embodiment of the present disclosure, an electromagnetic apparatus such as electromagnetic apparatus **200** is utilized to remove one or more mLED device structures **810** from an adhesion layer and placed onto an assembly substrate, as illustrated in FIGS. **15**A-**15**F.

FIG. **15**A illustrates a cross sectional view of an electromagnetic apparatus **300** directed in the negative Z direction

(as denoted by arrow **1501**) toward structure **1400**. In the illustrative embodiment, electromagnetic apparatus **300** has one head structure **212** (inside dashed box) that will subsequently make contact with uppermost surface **806**A of an mLED device structure, for example, mLED device structure **810**B. In an embodiment, head structure **212** has width W_{HS}, that is same or substantially same as width W_{MD}, of mLED device structure **810**B.

FIG. **15**B illustrates a cross sectional view of the structure of FIG. **15**A after head structure **212** of electromagnetic apparatus **300** is in physical contact with mLED device structure **810**B. After contact, electromagnet **122** is energized and magnetic flux **1503** (dashed line) is generated. Portions of magnetic flux **1503** is confined to magnetic structures **210**A and **210**B and forms a closed loop through cap **806**, as illustrated. Magnetic flux **1503** may be sufficiently confined within magnetic structures **210**A and **210**B and cap **806** and may not attract any of adjacent mLED device structure **810**A or **810**B.

As illustrated, when head structure **212** makes contact with mLED device structure **810**, portions of magnetic structure **210**A and **210**B are separated from adjacent mLED device structures **810**A and **810**B by gap G_{HL}. In an embodiment, gap G_{HL} is approximately half the thickness T_{MD}, of mLED device structure **810**. In an embodiment, gap G_{HL} that is at least equal to $(\frac{1}{2})T_{MD}$, accommodates thickness variations in mLED device structure **810** and ensures that electromagnetic apparatus **300** only contacts a single mLED device structure **810** during operation.

FIG. **15**C illustrates a cross sectional view of the structure of FIG. **15**B after electromagnetic apparatus **300** is raised in the positive Z direction (as denoted by arrow **1505**) and removed. The magnetic coupling strength between head structure **212** and mLED device structure **810**B is greater than an adhesive force between mLED device structure **810**B and adhesion layer **1302**. As a result, mLED device structure **810**B is detached from adhesion layer **1302** when electromagnetic apparatus **300** is moved.

FIG. **15**D illustrates a cross sectional view of electromagnetic apparatus **300** and mLED device structure **810**B directed in the negative Z direction (as denoted by arrow **1501**) towards adhesion layer **1502** on assembly substrate **1500**. In an embodiment, adhesion layer **1502** includes a material that is substantially similar to adhesion layer **1302**. In an embodiment, adhesion layer **1502** includes a UV light-sensitive material. Assembly substrate **1500** may include a material that is same or substantially same as the material of substrate **118**.

FIG. **15**E illustrates a cross sectional view of the structure of FIG. **15**D after mLED device structure **810**B is placed on adhesion layer **1502**. Adhesion layer **1502** has a known adhesion strength and mLED device structure **810**B is secured on the surface of adhesion layer **1502** after contact. Electromagnetic apparatus **300** is then deactivated. mLED device structure **810**B is then released from electromagnetic apparatus **300**, such that mLED device structure **810**B is decoupled from head structure **212**.

After electromagnetic apparatus **300** is deactivated and raised in the positive Z direction (as denoted by arrow **1505**), mLED device structure **810**B remains on adhesion layer **1502** of assembly substrate **1500** as shown in FIG. **15**F.

The method to remove a particular type of mLED device structure **810** from intermediate substrate **1300** and placed on assembly substrate **1500** has been described above in association with FIG. **15**A-**15**F. In an embodiment, same or substantially same method can be applied to remove one or more mLED device structures other than mLED device structure **810** from one or more substrates other than substrate **1300** and then placed adjacent to mLED device structure **810**B on adhesion layer **1502**.

FIG. **16**A is a cross-sectional illustration of a plurality of mLED structures **1610** formed above layer **802** that is formed above substrate **1600**. Substrate **1600** is different from the substrate **800**. In an embodiment, mLED device structure **1610** includes mLED **1604** and cap **1606** formed above mLED **1604**. In an embodiment, mLED device structure **1610** has one or more features of mLED device structure **810**, for example, having a width W_{MD}, and thickness T_{MD}. mLED device structure **1610** may be of a different color from a color of mLED device structures **810**. In an embodiment, cap **1606** includes a material that is same or substantially same as the material of cap **806**. mLED **1604** is fabricated using techniques similar to the fabrication of mLED **804**. In an embodiment, substrate **1600** includes a material such as sapphire or silicon.

FIG. **16**B is a plan-view illustration of the structure of FIG. **16**A. An array including a plurality of mLED device structures **1610** are depicted. Also shown is relative spacing W_{LX}, between adjacent mLED device structures **1610**A and **1610**B (along the X-axis). As shown, W_{LX} is a shortest distance between two adjacent sidewalls of two adjacent mLED device structures **1610**. In an illustrative embodiment, spacing along the X-axis between any two adjacent mLED device structures, for example, **1610**A and **1610**B is uniform. Any two adjacent mLED device structures, such as **1610**C and **1610**D may be separated along the Y-axis by an amount W_{LY}, as shown. In an embodiment, W_{LY} may be same or substantially same as W_{LX}.

After fabrication of the plurality of mLED device structures **1610**, a series of transfer operations are performed to transfer a plurality of mLED device structures **1610** to intermediate substrate **1700**. The transfer operations are same or substantially same as operations described in association with FIGS. **10**-**14**A. In an embodiment, the arrangement of mLED device structures **1610** on adhesion layer **1702** of an intermediate substrate **1700** after the transfer process is illustrated in cross-sectional illustration of FIG. **17**A and in the plan-view illustration of FIG. **17**B. In the illustrative embodiment, the arrangement of mLED device structures **1610** on adhesion layer **1702** is same or substantially same as the arrangement of mLED device structures **810** and spacing between mLED device structures **810** on adhesion layer **1302**.

FIG. **18**A is a cross-sectional illustration of a plurality of mLED structures **1810** on layer **802** that is formed above substrate **1800**. In an embodiment, mLED device structure **1810** includes mLED **1804** and cap **1806** formed above the mLED **1804**. In an embodiment, the mLED device structure **1810** has one or more features of mLED device structure **810** such as having width W_{MD}, and thickness T_{MD}. mLED device structure **1810** may be a different color from color of mLED device structures **810**. In an embodiment, cap **1806** includes material that is same or substantially same as material of the cap **806**. mLED **1804** is fabricated above substrate **1800** using techniques similar to fabrication of mLED **804**. In an embodiment, substrate **1800** includes a material such as silicon, glass or polymer.

FIG. **18**B is a plan-view illustration of the structure of FIG. **18**A. An array including a plurality of mLED device structures **1810** are depicted. Also shown is the relative spacing W_{LX}, between adjacent mLED device structure **1810**A and **1810**B (along the X-axis). As shown W_{LX}, is a shortest distance between two adjacent sidewalls of two adjacent mLED device structures **1810**. In the illustrative

embodiment, the spacing along the X-axis between any two adjacent mLED device structures, for example, **1810**A and **1810**B is uniform. Any two adjacent mLED device structures, such as **1810**C and **1810**D may be separated along the Y-axis by an amount W_{LY}, as shown. In an embodiment, W_{LY} may be same or substantially same as W_{LX}.

After fabrication of the plurality of mLED device structures **1810**, a series of transfer operations are performed to transfer a plurality of mLED device structures **1810** to an intermediate substrate **1900**. In an embodiment, transfer operations are same or substantially same as operations described in association with FIGS. **10-14**A. In an embodiment, the arrangement of mLED device structures **1810** on adhesion layer **1902** of intermediate substrate **1900** after the transfer process is illustrated in cross-sectional illustration of FIG. **19**A and in the plan-view illustration of FIG. **19**B. In the illustrative embodiment, the arrangement of mLED device structures **1810** on adhesion layer **1902** is same or substantially same as the arrangement of mLED device structures **810** and spacing between mLED device structures **810** on adhesion layer **1302**.

FIG. **20**A illustrates a cross sectional view of the structure of FIG. **15**F after the placement of mLED device structure **1610** adjacent to mLED device structure **810**B. It is to be appreciated that placing mLED device structure **1610** does not affect mLED device structure **810**B as the magnetic flux forms a closed loop through magnetic structure **210**A, cap **806** associated w mLED device structure **1610** and magnetic structure **210**B.

After placement of mLED device structure **1610**, electromagnet **122** is deactivated and electromagnetic apparatus **300** is raised and removed (method not shown).

FIG. **20**B illustrates a cross sectional view of the structure of FIG. **20**A after the placement of mLED device structure **1810** adjacent to mLED device structure **810**B. It is to be appreciated that placing mLED device structure **1810** does not affect mLED device structures **1610** or **810**B as the magnetic flux forms a closed loop through magnetic structure **210**A, cap **806** associated with mLED device structure **1810** and magnetic structure **210**B.

In an embodiment, mLED device structure **1810** has one or more features of mLED device structure **810**, or mLED device structure **1610** such as including cap **806** and having width W_{MD}, and thickness, T_{MD}. mLED device structure **1810** is of a different color than a color of mLED device structure **810**B, and mLED device structures **1610**.

FIG. **20**C illustrates a cross sectional view of the structure of FIG. **20**B after electromagnet **122** is deactivated and electromagnetic apparatus **300** is raised and removed. In an embodiment, three mLED device structure **810**B, **1610**, and **1810** are arranged laterally as shown. In an embodiment, there is a separation between the three mLED device structures **810**B, **1610** and **1810**, as shown. In other embodiments, the arrangement is such that centers of the three mLED device structures **810**B, **1610**, and **1810** each correspond to an apex of a triangle, as illustrated in FIG. **21**.

In an embodiment, intermediate substrates **1300**, **1700**, and **1900** each include a large collection of mLED device structures that require transfer to a host substrate, such as assembly substrate **1500**, depicted in FIGS. **20**A-**20**C. In such an example, an electromagnetic apparatus, such as electromagnetic apparatus **600** may be utilized to perform transfer of a large collection of mLED device structures **810**, **1610**, and **1810**.

FIGS. **22**A-**22**F illustrate a method to transfer a plurality of mLED device structures from an intermediate substrate to a host substrate.

FIG. **22**A illustrates a cross sectional view of electromagnetic apparatus **600** directed in the negative Z direction (as denoted by arrow **2200**) towards a plurality of mLED device structure **810** on an adhesion layer **1302**. In the illustrative embodiment, electromagnetic apparatus **600** has three head structures **630**A, **630**B and **630**C that will subsequently make contact with an uppermost surface **806**A of three corresponding mLED device structures **810**, such as mLED device structure **810**B, **810**D and **810**F. In an embodiment, each head structure **630**A, **630**B or **630**C has a width, W_{HS}, that is same or substantially same as the width, W_{MD}, of each mLED device structure **810**B, **810**D or **810**F.

FIG. **22**B illustrates a cross sectional view of the structure of FIG. **22**A after head structures **630**A, **630**B, and **630**C are in physical contact with mLED device structures **810**B, **810**D, and **810**F respectively. After contact, electromagnet **122** is energized, and magnetic flux **1503** (dashed line) is generated.

In an embodiment, the magnetic flux **1503** forms a closed loop through the magnetic structure portions **616**E and **622**A, head structure **630**A, magnetic structure portion **622**B, head structure **630**B, magnetic structure portion **622**C, head structure **630**C and through the magnetic structure portions **622**C and **616**F as shown. The magnetic flux **1503** may be sufficiently confined within the magnetic structure portions **616**A and **622**A, head structure **630**A, magnetic structure portion **622**B, head structure **630**B, magnetic structure portion **622**C, head structure **630**C and through the magnetic structure portions **622**C and **616**B and may not attract any mLED device structures immediately adjacent to mLED device structures **810**B, **810**D and **810**F.

As illustrated, when the head structures **630**A, **630**B, and **630**C make contact with mLED device structures **810**B, **810**D, and **810**F, respectively, magnetic structure portions **622**A, **622**B, **622**C, and **622**D are separated from mLED device structures that are not designed to be picked up. In an illustrative embodiment, mLED device structures **810**A, **810**C, **810**E, and **810**G are separated by gap G_{HL}, from the magnetic structure portions **622**A **622**B, **622**C and **622**D, respectively. In an embodiment, gap, G_{HL} is approximately at least half the thickness T_{MD}, of mLED device structure **810**. In an embodiment, gap G_{HL} that is equal to $(M)T_{MD}$ accommodates for extreme thickness variations in mLED device structure **810** and ensures that electromagnetic apparatus **600** only magnetically couples mLED device structure that are directly below the head structures **630**A, **630**B and **630**C during operation.

FIG. **22**C illustrates a cross sectional view of the structure of FIG. **22**B after electromagnetic apparatus **600** is lifted and removed. The magnetic coupling strength between head structures **630**A, **630**B, and **630**C and mLED device structures **810**B, **810**D, and **810**F, respectively, is greater than an adhesive force between mLED device structure **810**B, **810**D, and **810**F, and adhesion layer **1302**. As a result, mLED device structures **810**B, **810**D and **810**F, are removed from adhesion layer **1302** when electromagnetic apparatus **600** is raised (denoted by arrow **2210**) for example, in the positive Z-direction, as shown.

FIG. **22**D illustrates a cross sectional view of electromagnetic apparatus **600** and mLED device structures **810**B, **810**D. and **810**F, directed (as denoted by arrow **2230**) in the negative Z direction towards assembly substrate **1500** and adhesion layer **1502** on assembly substrate **1500**. In an embodiment, adhesion layer **1502** includes a material that is substantially similar to adhesion layer **1302**. In an embodiment, adhesion layer **1502** includes a material that is UV light sensitive.

FIG. **22**E illustrates a cross sectional view of the structure of FIG. **22**D after mLED device structures **810**B, **810**D, and **810**F, are placed on adhesion layer **1502**. Adhesion layer **1502** has a known adhesion strength and mLED device structures **810**B, **810**D, and **810**F, are secured on the surface of adhesion layer **1502** after contact. Electromagnetic apparatus **600** is then deactivated. mLED device structure **810**B is then released from electromagnetic apparatus **600**, such that mLED device structures **810**B, **810**D, and **810**F are decoupled from head structures **630**A, **630**B, and **630**C, respectively.

Electromagnetic apparatus **600** is then raised (denoted by arrow **2240**) for example, in the positive Z-direction, as shown. mLED device structures **630**A, **630**B, and **630**C, remains on adhesion layer **1502** of assembly substrate **1502** as shown in FIG. **22**F.

The method described above in association with FIG. **22**A-**22**F, can be applied to removing a plurality of mLED device structures from substrates other than substrate **1300** and placed adjacent to mLED device structures **810**B, **810**D, and **810**F. Depending on the number of head structures of an electromagnetic apparatus, a large collection of mLED device structures can be transferred from an intermediate substrate to host substrate **1500**.

FIG. **23**A illustrates the structure of FIG. **22**D following the placement of mLED device structure **1610** and mLED device structure **1810** adjacent to each mLED device structures **810**B, **810**D, and **810**F using electromagnetic apparatus **600**. In an embodiment, the placement is performed by using the method described above in association with FIGS. **22**A-**22**F.

In an embodiment, a plurality of mLED device structures **1610** are first removed from adhesion layer **1702** (depicted in FIGS. **17**A and **17**B) using electromagnetic apparatus **600**. The plurality of mLED device structures **1610** all have same size or substantially same size as mLED device structures **810**B, **810**D, and **810**F. In an embodiment, the plurality of mLED device structures **1610** that are removed also have the same spacing between mLED device structures **1610**, because the same electromagnetic apparatus **600** is utilized. In another embodiment mLED device structures **810**B, **810**D, and **810**F may have different sizes and spatial distribution. In some such embodiments, a different electromagnetic apparatus **600** is utilized for each type of mLED devices.

Subsequently, the plurality of mLED device structures **1610** are simultaneously placed on adhesion layer **1502** such that a single mLED device structure **1610** from the plurality of mLED device structures **1610** is adjacent to each of mLED device structures **810**B, **810**D, and **810**F as shown in FIG. **23**A. It is to be appreciated that the process of placing device structures **1610** adjacent to a corresponding mLED device structure **810**B, **810**D, or **810**F does not impact mLED device structure **810**B, **810**D, or **810**F.

In one such embodiment, the method (described in association with FIGS. **22**A-**22**F) is continued to remove a plurality of mLED device structures **1810** from adhesion layer **1902** (illustrated in FIGS. **19**A and **19**B) using electromagnetic apparatus **600**. The plurality of mLED device structures **1810** all have same or substantially same size as mLED device structures **810**B, **810**D, and **810**F. In an embodiment, the plurality of mLED device structures **1810** that are removed also have same spacing as spacing between mLED device structures **810**B, **810**D, and **810**F.

Subsequently, the plurality of mLED device structures **1810** are simultaneously placed on adhesion layer **1502** such that a single mLED device structure **1810** from the plurality of mLED device structures **1810** is adjacent to mLED device structures **810**B, **810**D, and **810**F as shown in FIG. **23**. In the illustrative embodiment, each of mLED device structures **810**B, **810**D, or **810**F is between mLED device structure **1610** and mLED device structure **1810**. It is to be appreciated that the process of placing each of the device structures **1810** adjacent to a corresponding mLED device structure **810**B, **810**D, or **810**F does not impact mLED device structure **810**B, **810**D, or **810**F.

In other embodiments, the arrangement of the different mLED device structures leads to a formation of a cluster of mLED device structures. For example, within the cluster centers of each of the three mLED device structures correspond to an apex of a triangle as illustrated in FIG. **23**B. In an illustrative embodiment, mLED device structures **810**B, **1610**, and **1810** form a first cluster, mLED device structures **810**D, **1610**, and **1810** form a second cluster and mLED device structures **810**F, **1610**, and **1810** form a third cluster.

While the arrangement between each mLED device structure within a cluster may not be linear such as is depicted in FIG. **23**A, the relative spacing between any two mLED device structures from two corresponding adjacent clusters is maintained after transferring from an intermediate substrate to a host substrate.

FIG. **24** illustrates a flow diagram depicting method **2400** to transfer mLED device structures from a substrate to an assembly substrate in accordance with embodiments of the present disclosure. The method begins at operation **2405** by providing a device structure on a first layer over a first substrate as depicted in the cross-sectional illustration of FIG. **10**. The method continues at operation **2410** by placing an electromagnet in contact with a plurality of mLED device structures and activating the electromagnet and attracting the device structures to a surface of the electromagnet proximal to the device structures, as depicted in the cross-sectional illustration of FIG. **11**. Method **2400** continues at operation **2415** by immersing the substrate and the device structures in a chemical solution, as depicted in the cross-sectional illustration of FIG. **12**A. Method **2400** continues at operation **2420** by chemically dissolving and removing the first layer between the device structures and the first substrate, as depicted in the cross-sectional illustration of FIG. **12**C. Method **2400** continues at operation **2425** by removing device structures adjacent to the surface of the electromagnet from the chemical solution, as depicted in the cross-sectional illustration of FIG. **12**D. Method **2400** continues at operation **2430** by providing a substrate having a first adhesion layer and placing the device structures on a first adhesion layer as depicted in the cross-sectional illustration of FIG. **13**. Method **2400** continues at operation **2435** by deactivating and removing the electromagnet, wherein the device structures adhere to the first adhesion layer as depicted in the cross-sectional illustration of FIG. **14**A. Method **2400** continues at operation **2440** by placing an electromagnetic apparatus comprising head structures directly over the device structures, as depicted in the cross-sectional illustration of FIG. **22**A. Method **2400** continues at operation **2445** by activating the electromagnetic apparatus and magnetically coupling device structures proximal to the head structures as depicted in the cross-sectional illustration of FIG. **22**B. Method **2400** continues at operation **2450** by lifting and removing the device structures proximal to the head structures from the first adhesion layer as depicted in the cross-sectional illustration of FIG. **22**C. Method **2400** continues at operation **2455** by placing the device structures proximal to the head structures onto a second adhesion layer over a third substrate and de-activating the electromagnetic

apparatus as depicted in the cross-sectional illustration of FIG. **22**E. Method **2400** concludes at operation **2460** by removing the electromagnetic apparatus from the third substrate, as depicted in the cross-sectional illustration of FIG. **22**F.

FIG. **25** illustrates a computing device with machine-readable storage media that stores instructions for performing one or more methods to transfer mLED device structures from a native substrate to an assembly substrate, in accordance with some embodiments of the disclosure.

Elements of embodiments (e.g., flowchart **2400**, and scheme described with reference to various figures) are also provided as a machine-readable medium (e.g., memory) for storing the computer-executable instructions (e.g., instructions to implement any other processes discussed herein). In some embodiments, computing platform **2510** comprises memory **2520**, Processor **2530**, machine-readable storage media **2540** (also referred to as tangible machine readable medium), communication interface **2560** (e.g., wireless or wired interface), and network bus **2570** coupled together as shown and with the electromagnetic apparatus **2550** (e.g., electromagnetic apparatus **600**).

In some embodiments, Processor **2530** is a Digital Signal Processor (DSP), an Application Specific Integrated Circuit (ASIC), a general purpose Central Processing Unit (CPU), or a low power logic implementing a simple finite state machine to perform the method of flowchart **2400**, and scheme described with reference to various figures, etc.

In some embodiments, the various logic blocks of system **500** are coupled together via Network Bus **2570**. Any suitable protocol may be used to implement Network Bus **2570**. In some embodiments, Machine-Readable Storage Medium **2540** includes Instructions (also referred to as the program software code/instructions) for performing one or more methods to transfer mLED device structures from a native substrate to an assembly substrate as described with reference to various embodiments and flowchart.

Program software code/instructions associated with flowchart **2400** (and/or various embodiments) and executed to implement embodiments of the disclosed subject matter may be implemented as part of an operating system or a specific application, component, program, object, module, routine, or other sequence of instructions or organization of sequences of instructions referred to as "program software code/instructions," "operating system program software code/instructions," "application program software code/instructions," or simply "software" or firmware embedded in processor. In some embodiments, the program software code/instructions associated with flowchart **2400** (and/or various embodiments) are executed by system **2500**.

In some embodiments, the program software code/instructions associated with flowchart **2400** (and/or various embodiments) are stored in a computer executable storage medium **2540** and executed by Processor **2530**. Here, computer executable storage medium **2540** is a tangible machine-readable medium that can be used to store program software code/instructions and data that, when executed by a computing device, causes one or more processors (e.g., Processor **2530**) to perform a method(s) as may be recited in one or more accompanying claims directed to the disclosed subject matter.

The tangible machine readable medium **2540** may include storage of the executable software program code/instructions and data in various tangible locations, including for example ROM, volatile RAM, non-volatile memory and/or cache and/or other tangible memory as referenced in the present application. Portions of this program software code/instructions and/or data may be stored in any one of these storage and memory devices. Further, the program software code/instructions can be obtained from other storage, including, e.g., through centralized servers or peer to peer networks and the like, including the Internet. Different portions of the software program code/instructions and data can be obtained at different times and in different communication sessions or in the same communication session.

The software program code/instructions (associated with flowcharts **2400** and other embodiments) and data can be obtained in their entirety prior to the execution of a respective software program or application by the computing device. Alternatively, portions of the software program code/instructions and data can be obtained dynamically, e.g., just in time, when needed for execution. Alternatively, some combination of these ways of obtaining the software program code/instructions and data may occur, e.g., for different applications, components, programs, objects, modules, routines or other sequences of instructions or organization of sequences of instructions, by way of example. Thus, it is not required that the data and instructions be on a tangible machine readable medium **2540** in entirety at a particular instance of time.

Examples of tangible computer-readable media **2540** include but are not limited to recordable and non-recordable type media such as volatile and non-volatile memory devices, read only memory (ROM), random access memory (RAM), flash memory devices, floppy and other removable disks, magnetic storage media, optical storage media (e.g., Compact Disk Read-Only Memory (CD ROMS), Digital Versatile Disks (DVDs), etc.), among others. The software program code/instructions may be temporarily stored in digital tangible communication links while implementing electrical, optical, acoustical or other forms of propagating signals, such as carrier waves, infrared signals, digital signals, etc. through such tangible communication links.

In general, tangible machine readable medium **2540** includes any tangible mechanism that provides (i.e., stores and/or transmits in digital form, e.g., data packets) information in a form accessible by a machine (i.e., a computing device), which may be included, e.g., in a communication device, a computing device, a network device, a personal digital assistant, a manufacturing tool, a mobile communication device, whether or not able to download and run applications and subsidized applications from the communication network, such as the Internet, e.g., an iPhone®, Galaxy®, Blackberry® Droid®, or the like, or any other device including a computing device. In one embodiment, processor-based system is in a form of or included within a PDA (personal digital assistant), a cellular phone, a notebook computer, a tablet, a game console, a set top box, an embedded system, a TV (television), a personal desktop computer, etc. Alternatively, the traditional communication applications and subsidized application(s) may be used in some embodiments of the disclosed subject matter.

Furthermore, the particular features, structures, functions, or characteristics may be combined in any suitable manner in one or more embodiments. For example, a first embodiment may be combined with a second embodiment anywhere the particular features, structures, functions, or characteristics associated with the two embodiments are not mutually exclusive.

While the disclosure has been described in conjunction with specific embodiments thereof, many alternatives, modifications and variations of such embodiments will be apparent to those of ordinary skill in the art in light of the foregoing description. The embodiments of the disclosure

are intended to embrace all such alternatives, modifications, and variations as to fall within the broad scope of the appended claims.

In a first example, an electromagnetic apparatus includes a first structure including non-magnetic material, a second structure including dielectric, where the second structure is above a first portion of the first structure. The electromagnetic apparatus further includes a third structure including a first sidewall portion adjacent to a first sidewall of the second structure and above a second portion of the first structure, where the first sidewall portion includes a magnetic material. The third structure further includes a second sidewall portion adjacent to a second sidewall of the second structure opposite to the first sidewall of the second structure, where the second sidewall portion is above a third portion of the first structure and an electromagnet is below and coupled with the third structure.

In second example, for any of first examples, the third structure includes a magnetic material including one or more of: mu-alloy, perma-alloy, cobalt, iron, nickel, alloy of iron and nickel, or an alloy of two or more of cobalt, iron or nickel.

In third example, for any of the first through second examples, the magnetic material has a permeability greater than 50.

In fourth example, for any of the first through third examples, the second structure has a first width along a first direction, the first sidewall portion has a second width along the first direction and the second sidewall portion has a third width along the first direction.

In fifth example, for any of the first through fourth examples, the first width is less than the second or the third widths.

In sixth example, for any of the first through fifth examples, the first width is between 20% to 30% of the combined total of the first, the second and the third widths.

In seventh example, for any of the first through sixth examples, the combined total of the first, the second and the third widths is between 100 nm-2 micron.

In eighth example, for any of the first through seventh examples, the first structure includes a metal or a metal alloy and has a thickness between 100 nm and 200 nm.

In ninth example, for any of the first through eighth examples, top surfaces of the first sidewall portion, the second sidewall portion and the second structure are co-planar.

In tenth example, for any of the first through ninth examples, the second structure includes a dielectric material including silicon and oxygen, silicon and carbon or silicon and nitrogen.

In eleventh example, for any of the first through tenth examples, the first sidewall and the second sidewall of the second structure are substantially vertical relative to a bottom surface of the second structure.

In twelfth example, an electromagnetic apparatus, includes a first structure including a non-magnetic material, a second structure including a dielectric on a first portion of the first structure. The electromagnetic apparatus further includes a third structure including a first magnetic structure adjacent to a first sidewall of the second structure, where the first magnetic structure extends continuously onto a second portion of the first structure and adjacent to a first sidewall of the first structure. The third structure further includes a second magnetic structure adjacent to a second sidewall of the second structure, opposite to the first sidewall, where the second magnetic structure extends onto a third portion of the first structure and on a second sidewall of the first structure and an electromagnet is below and coupled with the third structure.

In thirteenth example, for any of the twelfth examples, the first magnetic structure and second magnetic structure include a same magnetic material.

In a fourteenth example, for any of the twelfth through thirteenth examples, the first magnetic structure adjacent to the first sidewall of the second structure has a width that is the same as a thickness of the first magnetic structure extending continuously onto a second portion of the first structure.

In a fifteenth example, for any of the twelfth through fourteenth examples, the second magnetic structure adjacent to the second sidewall of the second structure has a width that is the same as a thickness of the first magnetic structure extending continuously onto a second portion of the first structure.

In sixteenth example, for any of the twelfth through fifteenth examples, the first magnetic structure adjacent to the first sidewall of the second structure has a width that is the same as a width of the second magnetic structure adjacent to the second sidewall of the second structure.

In seventeenth example, for any of the fifteenth through sixteenth examples, the second structure has a height that is less than a height of the first structure.

In eighteenth example, for any of the fifteenth through seventeenth examples further includes an encapsulation on a top surface of the second structure, on the third structure and on sidewalls of first structure not laterally adjacent to the third structure.

In nineteenth example, an electromagnetic apparatus includes a first structure including a non-magnetic material, a second structure including a dielectric material on a first portion of the first structure a third structure including the dielectric material on a second portion of the first structure and a fourth structure. The fourth structure includes a first magnetic structure adjacent to a first sidewall of the second structure, where the first structure extends continuously onto a third portion of the first structure and adjacent to a first sidewall of the first structure. The fourth structure further includes a second magnetic structure adjacent to a first sidewall of the third structure, where the second magnetic structure extends onto a fourth portion of the first structure and on a second sidewall of the first structure. The fourth structure further includes a third magnetic structure adjacent to a second sidewall of the second structure, adjacent to a second sidewall of the third structure and extends continuously onto a fifth portion of the first structure between the second sidewall of the second structure and the second sidewall of the third structure. The fourth structure further includes an electromagnet below and coupled with the fourth structure.

In a twentieth example, for any of the nineteenth examples, the second structure and the third structure have uppermost surfaces that are co-planar.

In twenty first example, for any of the twentieth example, a method of making an electromagnetic apparatus includes forming a first structure including a non-magnetic material. The method further includes forming a magnetic structure on sidewalls of the first structure and forming a dielectric layer on the first structure and patterning the dielectric layer to form an isolation structure. The method further includes forming a first magnetic layer on the first structure, adjacent to the isolation structure and on portions of the magnetic

structure and formation of a second magnetic layer on sidewalls of the isolation structure and on portions of the first magnetic layer.

In twenty second example, for any of the twentieth through twenty first examples, where forming the first structure includes forming a base structure including a non-magnetic material and forming a core structure including the non-magnetic material on a portion of the base structure.

In twenty third example, for any of the twentieth through twenty second examples, where forming the core structure includes forming sidewalls with vertical profiles.

In twenty fourth example, for any of the twentieth through twenty third examples, where the method further includes planarizing top portions of the isolation structure and top portion of the second magnetic layer to form top surfaces of the isolation structure and the second magnetic layer that are coplanar.

In a twenty fifth example, a method for transferring micro-devices, the method includes providing a device structure on a first layer over a first substrate and positioning an electromagnetic apparatus directly over the device structure. The method further includes activating an electromagnet in the electromagnetic apparatus to generate and confine a magnetic flux into a magnetic structure of the electromagnetic apparatus and magnetically couple the device structure to a surface of the magnetic structure proximal to the device structure. The method further includes lifting and removing the device structure from the first substrate and placing the device structure on a second layer over a second substrate, where the second substrate is separate from the first substrate. The method further includes releasing the device structure from the electromagnet, such that the device structure is decoupled from the electromagnet.

In twenty sixth example, for any of twenty fifth examples, where positioning the electromagnetic apparatus includes physically contacting a top portion of the device structure.

In twenty seventh example, for any of the twenty fifth through twenty sixth examples, the magnetic flux couples a ferromagnetic portion of the device structure to the magnetic structure.

In twenty eighth example, for any of the twenty fifth through twenty seventh examples, where a coupling strength between the magnetic structure and the device structure is greater than an adhesive force between the device structure and the first layer.

In twenty ninth example, for any of the twenty fifth through twenty eighth examples, where placing the device structure on a second layer causes the device structure to adhere to the second layer.

In thirtieth example, for any of the twenty fifth through twenty ninth examples, where the device structure includes a light emitting diode.

In thirty first example, for any of the twenty fifth through thirtieth examples, the device structure is a first device structure, and the electromagnetic apparatus is a first electromagnetic apparatus, and the electromagnet is a first electromagnet and the method includes providing a second device structure on a third layer over a third substrate. The method further includes positioning the second electromagnetic apparatus directly over the device structure and activating a second electromagnet in the second electromagnetic apparatus, where the activating generates and confining a magnetic flux into a second magnetic structure of the second electromagnetic apparatus and magnetically coupling the second device structure to a surface of the second magnetic structure proximal to the second device structure. The method further includes lifting and removing the second device structure from the third substrate, placing the second device structure on the second layer over the second substrate adjacent to the first device structure and releasing the second device structure from the second electromagnet, such that the second device structure is decoupled from the second electromagnet.

In thirty second example, for any of the thirty first examples, the method further includes providing a third device structure on a fourth layer over a fourth substrate and positioning a third electromagnetic apparatus directly over the third device structure. The method further includes activating a third electromagnet in the third electromagnetic apparatus, where the activating generates and confines a magnetic flux into a third magnetic structure of the third electromagnetic apparatus and magnetically couples the third device structure to a surface of the third magnetic structure proximal to the third device structure. The method further includes lifting and removing the third device structure from the fourth substrate and placing the third device structure on the second layer over the second substrate adjacent to the first device structure and the second device structure. The method further includes releasing the third device structure from the third electromagnet, such that the third device structure is decoupled from the third electromagnet.

In thirty third example, for any of the thirty second examples, where the third electromagnetic apparatus is the same as the first electromagnetic apparatus and the second electromagnetic apparatus.

In thirty fourth example, for any of the twenty fifth through thirty second examples, where placing and releasing the third device structure does not affect the position of the first device structure or the second device structure.

In thirty fifth example, a method for transferring micro-devices includes providing device structures over a first substrate and positioning an electromagnetic apparatus including head structures directly over the device structures. The method further includes activating an electromagnet in the electromagnetic apparatus to generate a magnetic flux in the head structures and magnetically coupling device structures proximal to the head structures. The method further includes lifting and removing the device structures proximal to the head structures from the first substrate and placing the portion of the device structures proximal to the head structures onto a second substrate. The method further includes de-activating the electromagnet and removing the electromagnetic apparatus away from second substrate.

In thirty sixth example, for any of the thirty fifth example, where each head structure couples one device structure directly under the head structure.

In thirty seventh example, for any of the thirty fifth through thirty sixth examples, where the head structure makes a physical contact with the device structure.

In a thirty eighth example, for any of the thirty fifth through thirty seventh examples, where the device structures not directly under the head structures are not magnetically coupled and left on the first substrate.

In a thirty ninth example, for any of the thirty fifth through fourteenth examples, where the device structures not directly under the head structures do not come in contact with any portion of the electromagnetic apparatus.

In fortieth example, for any of the thirty fifth through thirty ninth examples, where the first substrate includes a first adhesion layer between the device structures and the first substrate, and the second substrate includes a second adhesion layer on the second substrate.

In forty first example, for any of the thirty fifth, where placing the device structures on the second substrate and deactivating the electromagnetic apparatus causes the head structures to be magnetically decoupled with the device structures.

In forty second example, a method for transferring micro-devices includes providing device structures on a first layer over a first substrate and placing an electromagnet over the device structure. The method further includes activating the electromagnet and attracting the device structures to a surface of the electromagnet proximal to the device structures. The method further includes immersing the first substrate and the device structures in a chemical solution and chemically dissolving and removing the first layer between the device structures and the first substrate. The method further includes removing the device structures adjacent to the surface of the electromagnet from the chemical solution and providing a second substrate having a first adhesive layer. The method further includes placing the device structures on a first adhesive layer, and deactivating and removing the electromagnet, where the device structures adhere to the first adhesive layer. The method further includes placing an electromagnetic apparatus including head structures directly over the device structures and activating the electromagnetic apparatus, to generate a magnetic flux in the head structures and magnetically couple device structures proximal to the head structures. The method further includes lifting and removing the device structures proximal to the head structures from the first adhesive layer, placing the device structures proximal to the head structures onto a second adhesive layer over a third substrate and de-activating and removing the electromagnetic apparatus from the third substrate.

In forty third examples, for any of the forty second example, where placing an electromagnet over the device structures causes a lowest surface of the electromagnet to come into contact with a top surface of a plurality of device structure.

In a forty fourth example, for any of the forty second through forty third example, where placing an electromagnet over the device structures causes a gap between the lowest surface of the electromagnet and a top surface of at least one device structure other than the plurality of device structures.

In forty fifth examples, for any of the forty second through forty fourth examples, where chemically dissolving and removing the first layer between the device structures and the first substrate causes the gap to be eliminated as the electromagnet pulls the at least one device structure to the lowest surface.

In forty sixth example, for any of the forty second through forty fifth examples, where a spacing between device structures remains unchanged after being placed on the first adhesive layer.

In forty seventh example, a machine-readable media having one or more instructions, that when executed, causes an apparatus to perform operations including providing a device structure on a first layer over a first substrate. The media further causes positioning an electromagnetic apparatus directly over the device structure and activating an electromagnet in the electromagnetic apparatus. The media further causes the electromagnet to generate and confine a magnetic flux into a magnetic structure of the electromagnetic apparatus and magnetically couple the device structure to a surface of the magnetic structure proximal to the device structure. The media further causes lifting and removing the device structure from the first substrate and placing the device structure on a second layer over a second substrate, where the second substrate is separate from the first substrate. The media further causes releasing the device structure from the electromagnet, such that the device structure is decoupled from the electromagnet.

In forty eighth example, for any of the forty seventh examples, where positioning the electromagnetic apparatus includes physically contacting a top portion of the device structure.

An abstract is provided that will allow the reader to ascertain the nature and gist of the technical disclosure. The abstract is submitted with the understanding that it will not be used to limit the scope or meaning of the claims. The following claims are hereby incorporated into the detailed description, with each claim standing on its own as a separate embodiment.

What is claimed is:

1. An electromagnetic apparatus, comprising:
- a first structure comprising a non-magnetic material;
- a second structure comprising a dielectric material on a first portion of the first structure;
- a third structure comprising the dielectric material on a second portion of the first structure;
- a fourth structure, comprising:
  - a first magnetic structure adjacent to a first sidewall of the second structure, the first magnetic structure extending continuously onto a third portion of the first structure and adjacent to a first sidewall of the first structure;
  - a second magnetic structure adjacent to a first sidewall of the third structure, the second magnetic structure extending onto a fourth portion of the first structure and on a second sidewall of the first structure; and
  - a third magnetic structure adjacent to a second sidewall of the second structure, adjacent to a second sidewall of the third structure and extending continuously onto a fifth portion of the first structure, the fifth portion between the second sidewall of the second structure and the second sidewall of the third structure; and
- an electromagnet below and coupled with the fourth structure.

2. The electromagnetic apparatus of claim **1**, wherein the second structure and the third structure have uppermost surfaces that are co-planar.

3. The electromagnetic apparatus of claim **1**, wherein the fourth structure comprises a magnetic material including one or more of: mu-alloy, perma-alloy, cobalt, iron, nickel, alloy of iron and nickel, or an alloy of two or more of cobalt, iron or nickel.

4. The electromagnetic apparatus of claim **3**, wherein the magnetic material has a permeability greater than 50.

5. The electromagnetic apparatus of claim **1**, wherein the second structure has a first width along a first direction, wherein the first magnetic structure adjacent to the first sidewall of the second structure has a second width along the first direction and the third magnetic structure adjacent to the second sidewall of the second structure has a third width along the first direction.

6. The electromagnetic apparatus of claim **5**, wherein the first width is less than the second or the third widths.

7. The electromagnetic apparatus of claim **6**, wherein the first width is between 20% to 30% of the combined total of the first, the second and the third widths.

8. The electromagnetic apparatus of claim **7**, wherein the combined total of the first, the second and the third widths is between 100 nm-2 microns.

9. The electromagnetic apparatus of claim 1, wherein the first structure comprises a metal or a metal alloy and has a thickness between 100 nm and 200 nm.

10. The electromagnetic apparatus of claim 1, wherein a top surface of the first magnetic structure adjacent to a first sidewall of the second structure, a top surface of the third magnetic structure adjacent to a second sidewall of the second structure and a top surface of the second structure are co-planar.

11. The electromagnetic apparatus of claim 1, wherein the second structure comprises a dielectric material including silicon and oxygen, silicon and carbon or silicon and nitrogen.

12. The electromagnetic apparatus of claim 1, wherein the first sidewall and the second sidewall of the second structure are substantially vertical relative to a bottom surface of the second structure.

13. The electromagnetic apparatus of claim 1, wherein the second magnetic structure adjacent to the first sidewall of the third structure has a width that is the same as a width of the third magnetic structure adjacent to the second sidewall of the third structure.

14. The electromagnetic apparatus of claim 1, wherein the first magnetic structure, the second magnetic structure and the third magnetic structure each comprise a same magnetic material.

15. The electromagnetic apparatus of claim 1, wherein the first magnetic structure adjacent to the first sidewall of the second structure has a width that is the same as a thickness of the first magnetic structure extending continuously onto a third portion of the first structure.

16. The electromagnetic apparatus of claim 1, wherein the second magnetic structure adjacent to the first sidewall of the third structure has a width that is the same as a thickness of the second magnetic structure extending continuously onto a fourth portion of the third structure.

17. The electromagnetic apparatus of claim 1, wherein the first magnetic structure adjacent to the first sidewall of the second structure has a width that is the same as a width of the second magnetic structure adjacent to the second sidewall of the second structure.

18. The electromagnetic apparatus of claim 1, further includes an encapsulation on a top surface of the second structure, on the third structure and on sidewalls of first structure not laterally adjacent to the third structure.

19. The electromagnetic apparatus of claim 1, wherein the electromagnetic apparatus is a first electromagnetic apparatus array, wherein the electromagnet is a first electromagnet and wherein the electromagnetic apparatus comprises a second electromagnetic array separated from the first electromagnetic apparatus array by a dielectric layer, the second electromagnetic array, comprising:

a fifth structure comprising a non-magnetic material;

a sixth structure comprising the dielectric material on a first portion of the fifth structure;

a seventh structure comprising the dielectric material on a second portion of the fifth structure;

an eighth structure, comprising:

a first magnetic structure adjacent to a first sidewall of the sixth structure, the first magnetic structure extending continuously onto a third portion of the fifth structure and adjacent to a first sidewall of the fifth structure;

a second magnetic structure adjacent to a first sidewall of the seventh structure, the second magnetic structure extending onto a fourth portion of the fifth structure and on a second sidewall of the fifth structure; and

a third magnetic structure adjacent to a second sidewall of the sixth structure, adjacent to a second sidewall of the seventh structure and extending continuously onto a fifth portion of the fifth structure, the fifth portion between the second sidewall of the sixth structure and the second sidewall of the seventh structure; and

a second electromagnet below and coupled with the eighth structure.

20. The electromagnetic apparatus of claim 19, wherein the first magnetic structure adjacent to the first sidewall of the fifth structure is coupled with the first magnetic structure adjacent to the first sidewall of the first structure by a fourth magnetic structure.

21. The electromagnetic apparatus of claim 20, wherein the first electromagnet and the second electromagnet are coupled.

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